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Advanced Microstrip Antenna Developments

Volume II: Microstrip GPS Antennas for General Aviation Aircraft

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16. Abstract

This report describes the application of microstrip antenna technology to the design of general aviation (G/A) aircraft antennas for use with the Global Positioning System (GPS).

For most G/A aircraft, only single frequency operation will be required. However, air-carrier and some large corporate aircraft may make use of dual-frequency operation. For this reason, some dual-frequency designs have been investigated.

The main effort was given to the design of antennas with broad beamwidths which could be switched or steered to compensate for aircraft maneuvers, with the goal of maintaining near-hemispherical carriage in flight. A hybrid microstrip crossed-slot and sleeve-dipole element used with a suitable combining network gives a suitable, controllable broad-beam pattern. This element and its performance are described. In addition, radiation patterns are presented using scale-model aircraft and simple crossed-slot antennas.

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PREFACE

The work described in this report is part of a series of activities in the development of microstrip antennas for aircraft use. The specific application has been in aircraft-satellite communications at L-band. These activities began in 1974 with the design and installation of both single elements and of electronically-steerable microstrip phased arrays on test aircraft. The antennas were sucessfully flown during the international test program with the NASA ATS-6 satellite. Work performed since then has stressed component improvement and array analysis pertinent to the aircraft application. The inherent low cost and simplicity of the microstrip technology also makes it suitable for G/A use with GPS. The work described in this volume was directed by the TSC Project Engineer, Leslie Klein.

ACKNOWLEDGEMENT

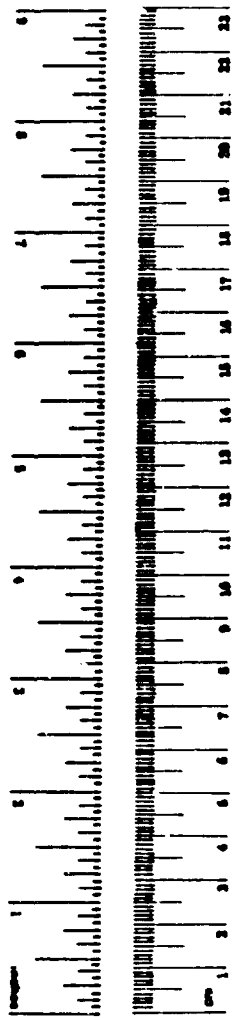
The Federal Aviation Administration and the Transportation Systems Center with to express their thanks to Mr. M. Gilreath of NASA Langley Research Center for his generosity in providing the scale-model aircraft used in the GPS antenna development.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

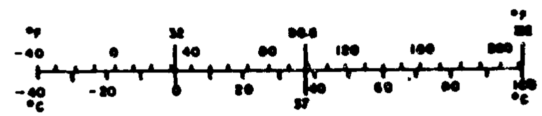


TABLE OF CONTENTS

Section	Title	Page
	PREFACE	iii
	ACKNOWLEDGEMENT	iii
1	INTRODUCTION	1
2	SCALE MODEL MEASUREMENTS	3
	2.1 Background	3
	2.2 Development of 1:7 Scale Model Element	3
	2.3 Mounting of Elements on Scale Model Aircraft	5
	2.4 Discussion of Test Results	5
3	DUAL-FREQUENCY CROSSED SLOT FOR GPS	15
4	STEERABLE BEAM GPS ANTENNA FOR GENERAL AVIATION AIRCRAFT	20
	4.1 Background	20
	4.2 Overview of Concepts	21
	4.2.1 Pyramid Array	21
	4.2.2 Wrapped Array of Crossed Slots	23
	4.2.3 Monopole on Crossed Slot	23
	4.3 Concept Tradeoffs	30
	4.4 Engineering-Model Measurements	34
	4.4.1 Construction Details	34
	4.4.2 Impedance Measurements	34
	4.4.3 Pattern Measurements	39
	4.4.4 Recommendations for Further Refinements	39

Appendix	Page
Report of New Technology	42

TABLES

Table	Title	Page
2-1	Percentage of Hemisphere Above Given Gain	14
4-1	Comparison of Approaches	32

ILLUSTRATIONS

Figure	Title	Page
2-1	Shallow Cavity Crossed-Slot	4
2-2	Antenna Positions on the Cessna 402B Model	6
2-3	Antenna Positions on the Piper Cherokee Model	7
2-4	Front Antenna Patterns from the Cessna 402B Model, 10,477 MHz	8
2-5	Rear Antenna Patterns from the Cessna 402B Model, 10,870 MHz	9
2-6	Front Antenna Patterns from the Cessna 150 Model, 10,447 MHz	10
2-7	Rear Antenna Patterns from the Cessna 150 Model, 10,870 MHz	11
2-8	Front Antenna Patterns from the Piper Cherokee Model, 10,828 MHz	12
2-9	Rear Antenna Patterns from the Piper Cherokee Model, 10,780 MHz	13
3-1	Dual-Frequency Crossed-Slot Antenna	16
3-2	Input Impedance for the Dual-Frequency Crossed-Slot	17
3-3	Radiation Pattern for the Dual-Frequency Crossed-Slot on a Square Ground Plan, 1575 MHz	18
3-4	Radiation Pattern for the Dual-Frequency Crossed-Slot on a Square Ground Plane, 1234.5 MHz	19
4-1	Pyramid Array	22
4-2	Radiation Pattern for a Single Element Tilted 45°, 1640 MHz	24
4-3	Monopole on a Crossed-Slot	25
4-4	Radiation Pattern for the Monopole on a Crossed-Slot	27
4-5	Monopole with a Circularly Polarized Element on a Raised Ground Plane	28
4-6	Sleeve Dipole on a Crossed-Slot	29
4-7	Radiation Pattern for the Sleeve Dipole on a Crossed-Slot	31
4-8	Microstrip Crossed-Slot and Phase-Shifter	35
4-9	Sleeve Dipole Over a Microstrip Crossed-Slot	36
4-10	Input Impedance with the Sleeve Dipole Off	37
4-11	Input Impedance with the Sleeve Dipole On	38
4-12	Pattern of the Sleeve Dipole/Crossed Slot Taken Through the Null	40
4-13	Pattern of the Sleeve Dipole/Crossed Slot Taken at Right Angles to the Null	41

1. INTRODUCTION

This document, Volume II of the final report "Advanced Microstrip Antenna Developments," describes the design and performance of several different antennas for general aviation (G/A) aircraft which show promise for use with the U.S. Department of Defense Global Positioning System (GPS). The basic characteristics of GPS are known, and will not be described here. The factors which affect antenna design for aircraft use with GPS are (1) the requirements for dual-frequency operation, for some users; and (2) the need for hemispherical coverage, at least, with reasonable gain to maximize the number of satellites in view.

For most G/A users, there will be no requirement for dual-frequency operation. However, some large corporate aircraft may wish to make use of the additional accuracy made available by the use of both GPS frequencies. Air carrier aircraft are also candidates for dual-frequency equipment. For this reason, some effort has been given to the design of a dual-frequency element, and for a non-steerable antenna. This has resulted in a simple, inexpensive structure.

The main effort, however, was given to the design of antennas with broad beamwidths which could be switched or steered to compensate for aircraft maneuvers, with the goal of maintaining near-hemispherical coverage for a range of aircraft flight orientations. Several approaches were devised including arrays or clusters out of which the best available element was selected by switching.

The best approach which has been devised is a hybrid element composed of a microstrip crossed slot and a sleeve dipole; the dipole is centered on the slot intersection. These two elements are combined in a microstrip network with independent control of relative phase and amplitude. By suitable choice of phase and amplitude, the combined elements form a broad beam which can be tilted in elevation and rotated in azimuth.

In addition, a set of radiation patterns has been taken using scale-model G/A aircraft provided by NASA Langley Research Center and a scaled version of

the crossed-slot element. These patterns give the coverage to be expected on a range of G/A aircraft using the simplest broad-beam elements, and also serve as a reference for measurements taken with a variety of full-size elements and array types on ground planes.

2. SCALE MODEL MEASUREMENTS

2.1 BACKGROUND

During this phase of the contract, measurements on scale-model aircraft were performed using scale-model crossed slot antennas. To confirm its effectiveness as a GPS element for general-aviation aircraft, three 1:7 scale-model airplanes were obtained from NASA Langley Research Center for pattern tests. A 1:7 model crossed slot was developed for use in taking radiation patterns on a Cessna 402B, a Cessna 150, and a Piper Cherokee aircraft model. Two element positions were used for each of the airplanes. Radiation Distribution Plots (RDP) were made for all configurations of aircraft and antenna position. The data from the RDPs were used to project the percentage of the hemisphere above the aircraft covered with a gain greater than 0 dBi. The measured patterns and RDP data from the three aircraft do not greatly differ from the element patterns on a flat ground plane. The aircraft patterns exhibit minor scattering from the tail section.

2.2 DEVELOPMENT OF 1:7 SCALE MODEL ELEMENT

Direct scaling of the microstrip crossed slot was not practical. The effect of reduced etching tolerances and the difficulty of producing reliable plated-through holes at 11.0 GHz create manufacturing problems which it is impractical to try to solve; a new element design approach was therefore considered as an alternative to 1:7 scaling.

To produce a reliable element design with patterns identical to the crossed slot, a cavity-backed slot was developed (Figure 2-1). This design consists of a turnstile arrangement of slot elements backed by a circular cavity. The cavity is excited by a microstrip disc of nearly elliptical shape. Fields produced by the elliptical disc excite the slots in phase quadrature to

produce circular polarization. A total of five of these elements was constructed and tuned for approximately 10.8 GHz. The axial ratio of the elements was approximately 2 dB.

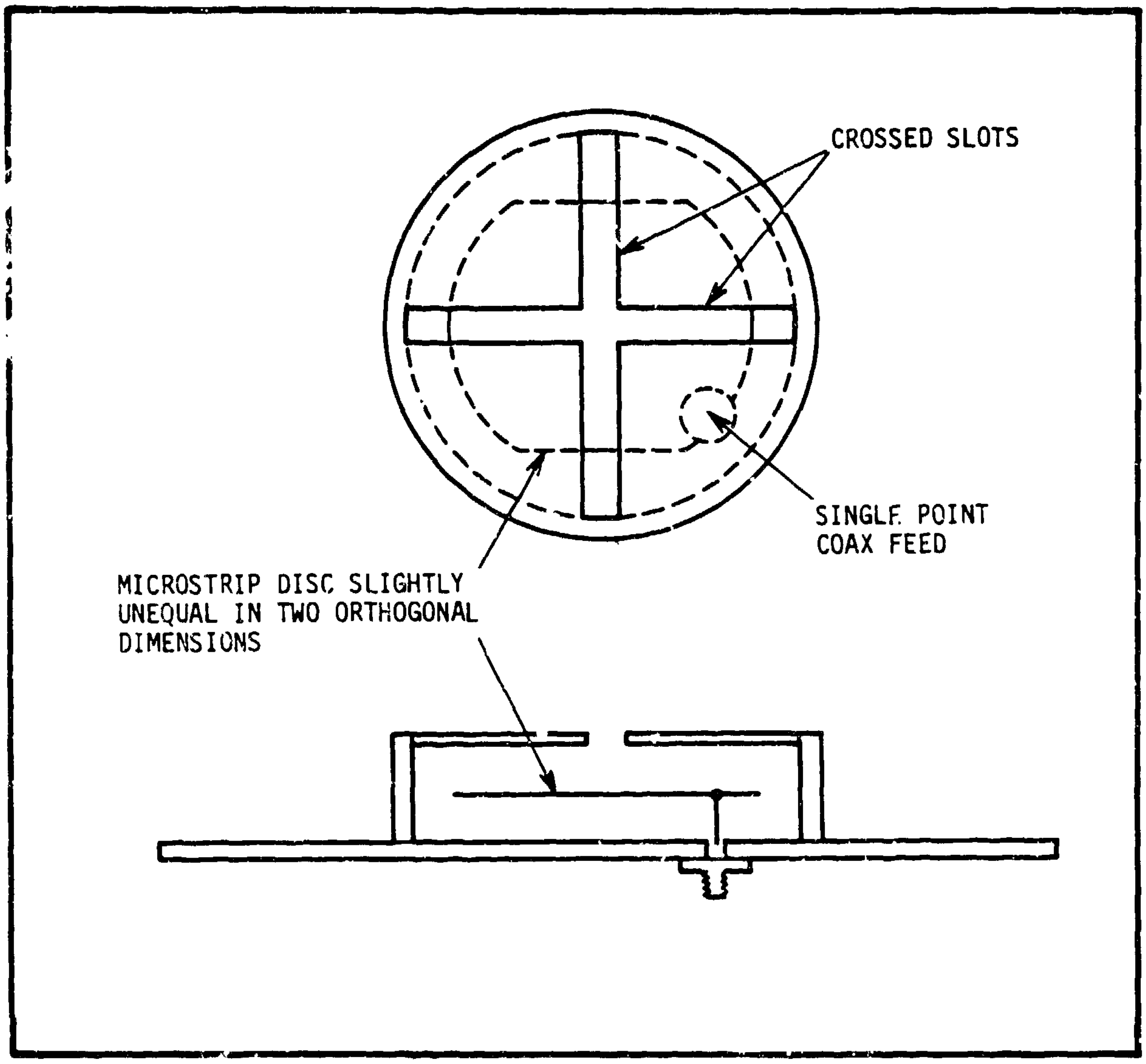


Figure 2-1 Shallow Cavity Crossed- Slot

One of the cavity-backed slot elements was mounted on a 7-inch ground plane to simulate the full-size crossed-slot patterns. Comparing these data with patterns of a microstrip crossed slot on a 4-foot ground plane gives an antenna gain to be used for the aircraft-model patterns.

2.3 MOUNTING OF ELEMENTS ON SCALE MODEL AIRCRAFT

Two antenna positions were tested on each of the aircraft models. The positions were on top of the fuselage and on the centerline of the aircraft body. Figure 2-2 shows the positions used on the Cessna 402B. The Piper Cherokee model is shown in Figure 2-3. During the pattern and RDP measurements, the unused element was covered with aluminum tape to eliminate interaction with the receiving antenna.

2.4 DISCUSSION OF TEST RESULTS

Radiation patterns in the pitch and roll planes are reproduced in Figures 2-4 through 2-9 for the Cessna 402B, the Cessna 150, and the Piper Cherokee, respectively. There was little difference in the radiation patterns and 0 dBi coverages between the forward and rear antenna positions. The shadowing caused by the aircraft tail is most visible in the Cessna 402B and the Piper Cherokee pitch-plane patterns. The roll-plane data demonstrated a wider beamwidth than the pitch plane in all cases. This is caused by the large ground-plane effect of the wings and the tail shadowing.

The predicted 0 dBi coverage of the hemisphere above the antenna is given in Table 2-1. The difference in the coverage from the front to rear positions is probably due to the measurement errors at 11 GHz. The coverage levels were adjusted by assuming all elements maintained a radiation efficiency of 0.875 or a loss of 0.6 dB. These data indicate that the crossed slot will perform well as a GPS antenna for use in general aviation. Coverage will be good to most satellite locations near the horizon with the possible exception of directly aft, through the tail, while the aircraft is in level flight.

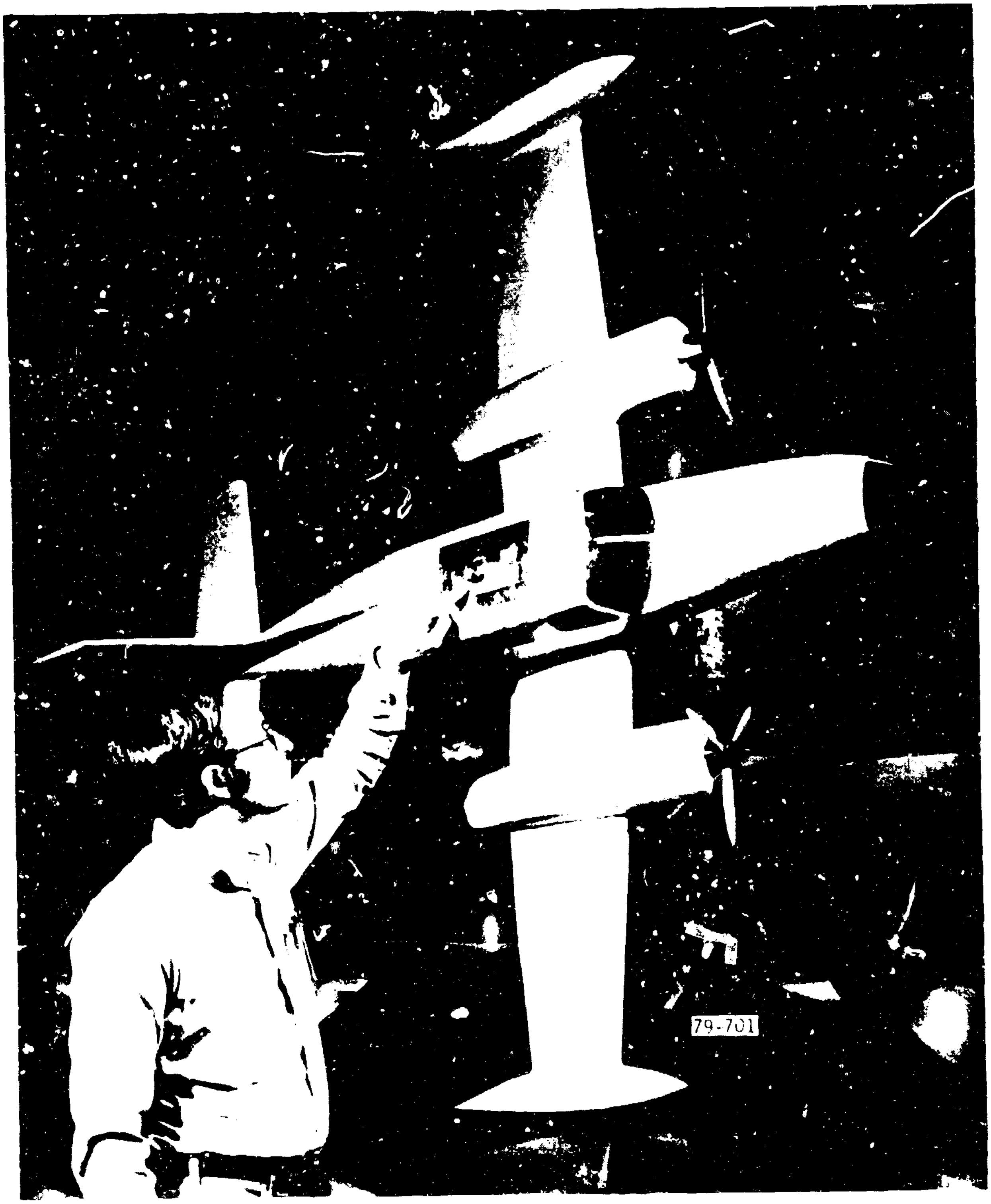


Figure 2-2 Antenna Positions on the Cessna 402B Model

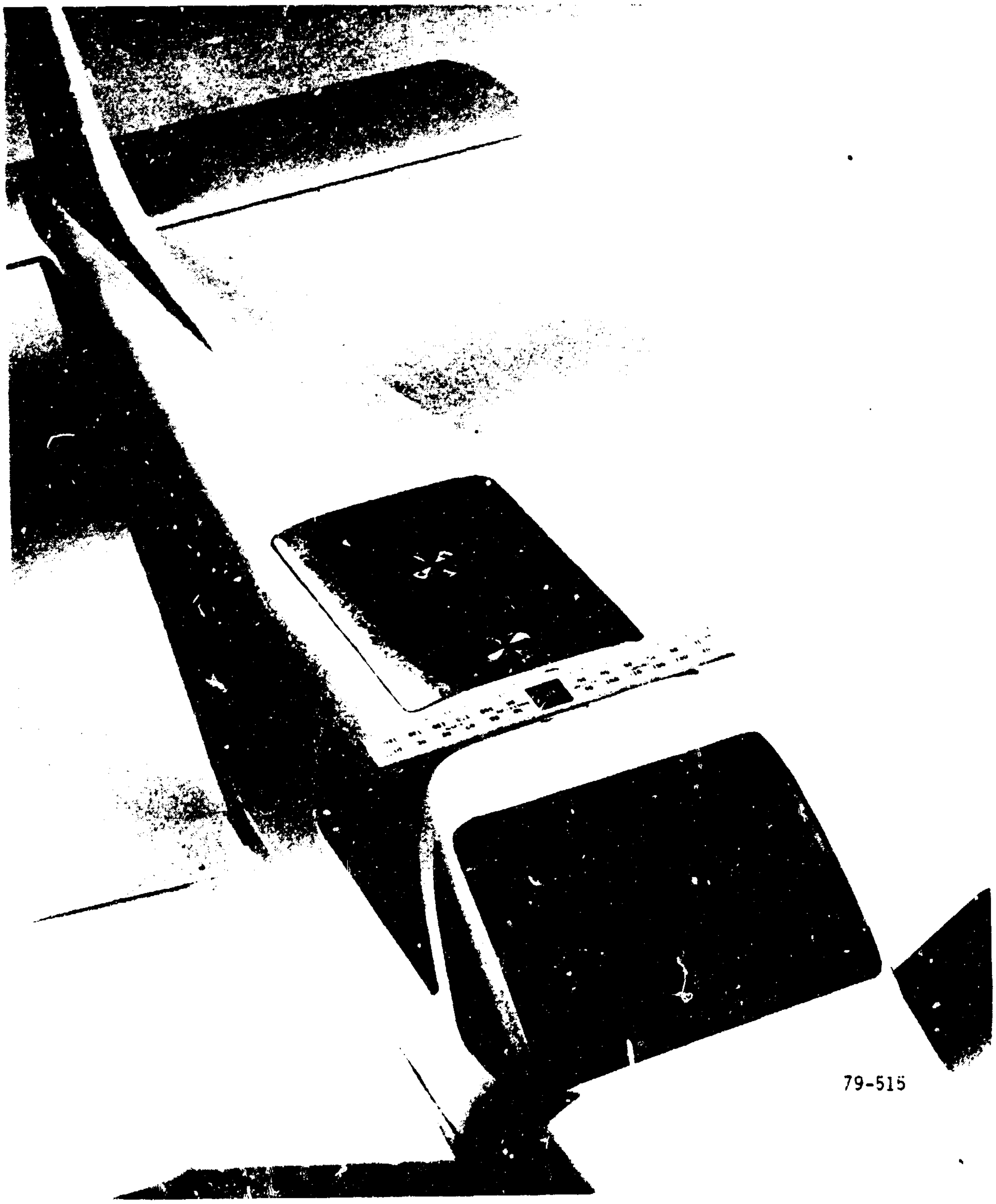


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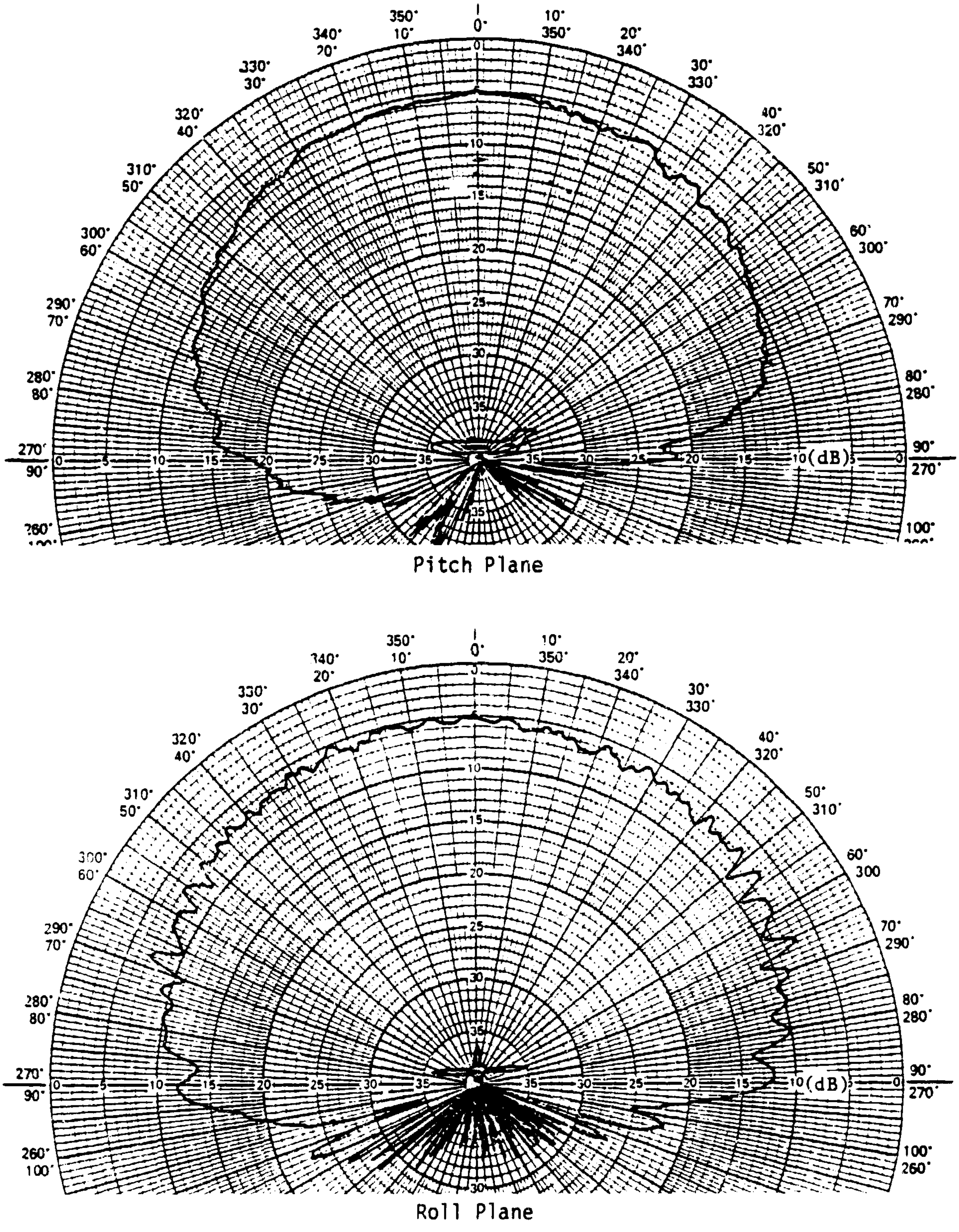
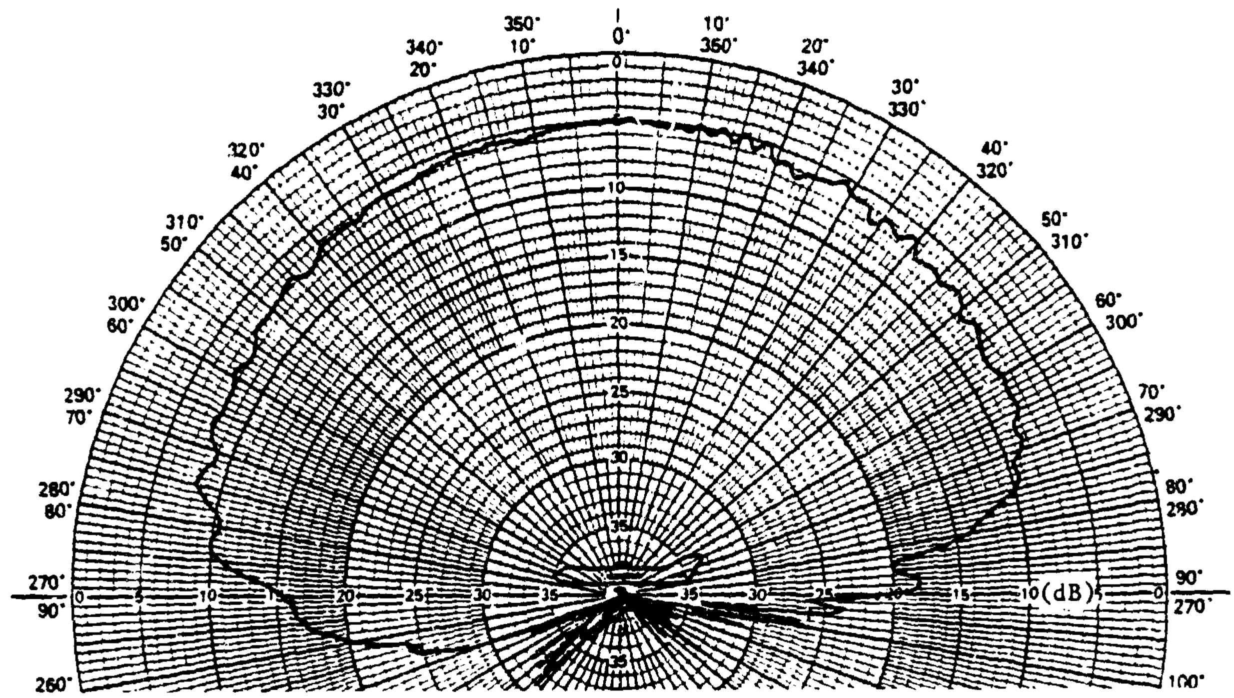
Figure 2-3 Antenna Positions on the Piper Cherokee Model



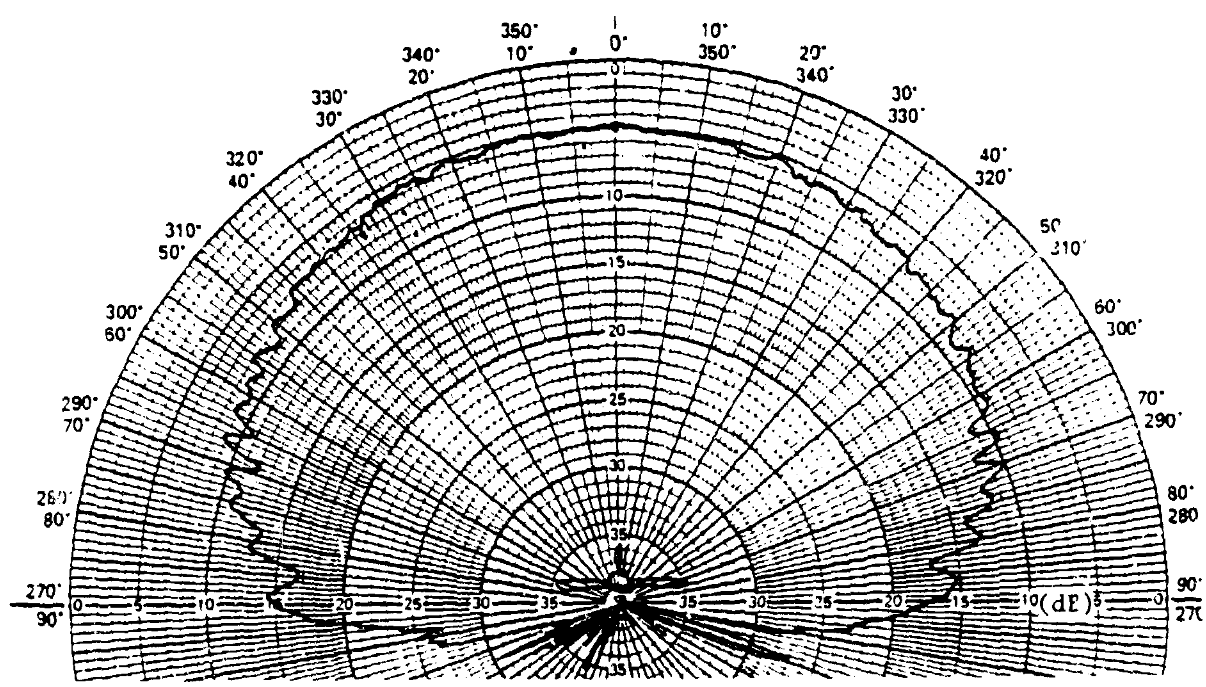
Pitch Plane

Roll Plane

Figure 2-4 Front Antenna Patterns from the Cessna 402B Model, 10,447 MHz

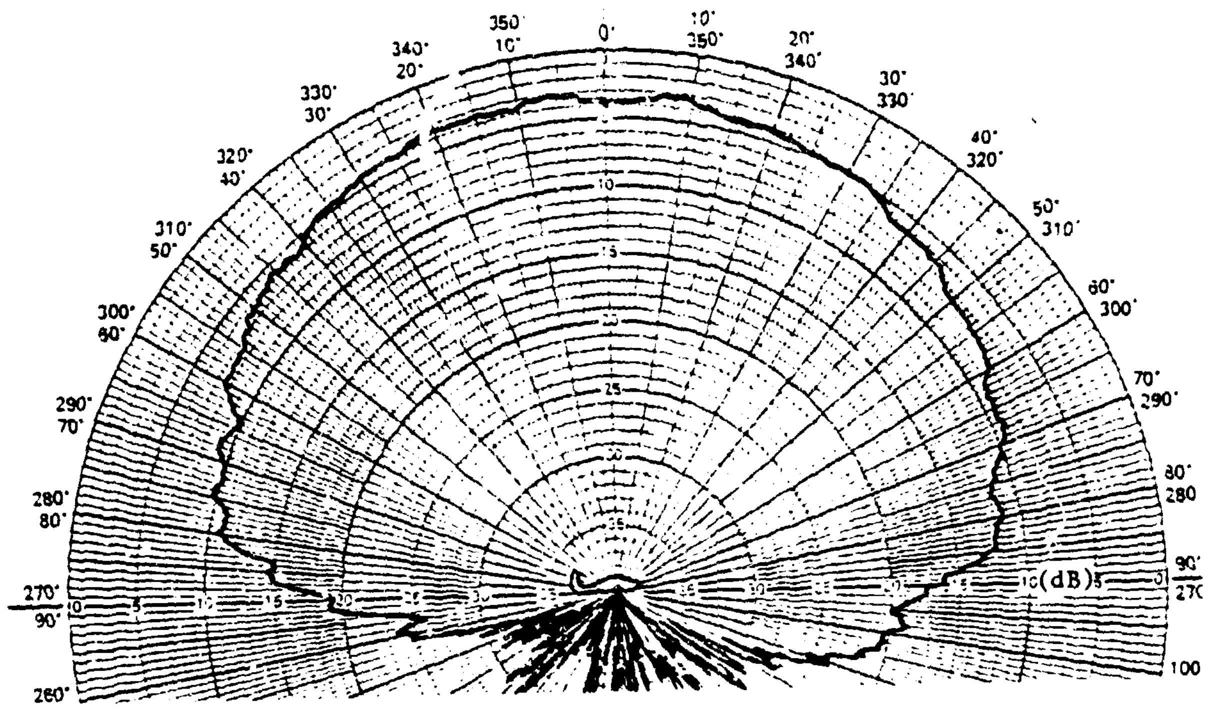


Pitch Plane

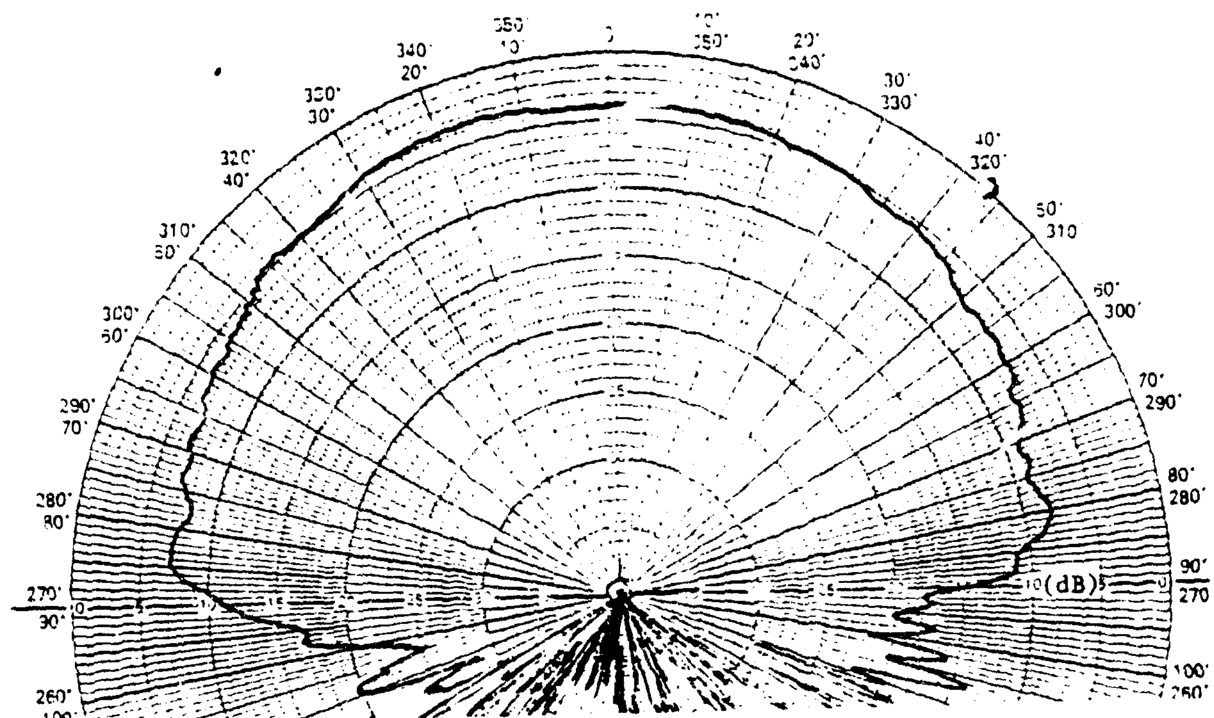


Roll Plane

Figure 2-5 Rear Antenna Patterns from the Cessna 402B Model, 10,870 MHz

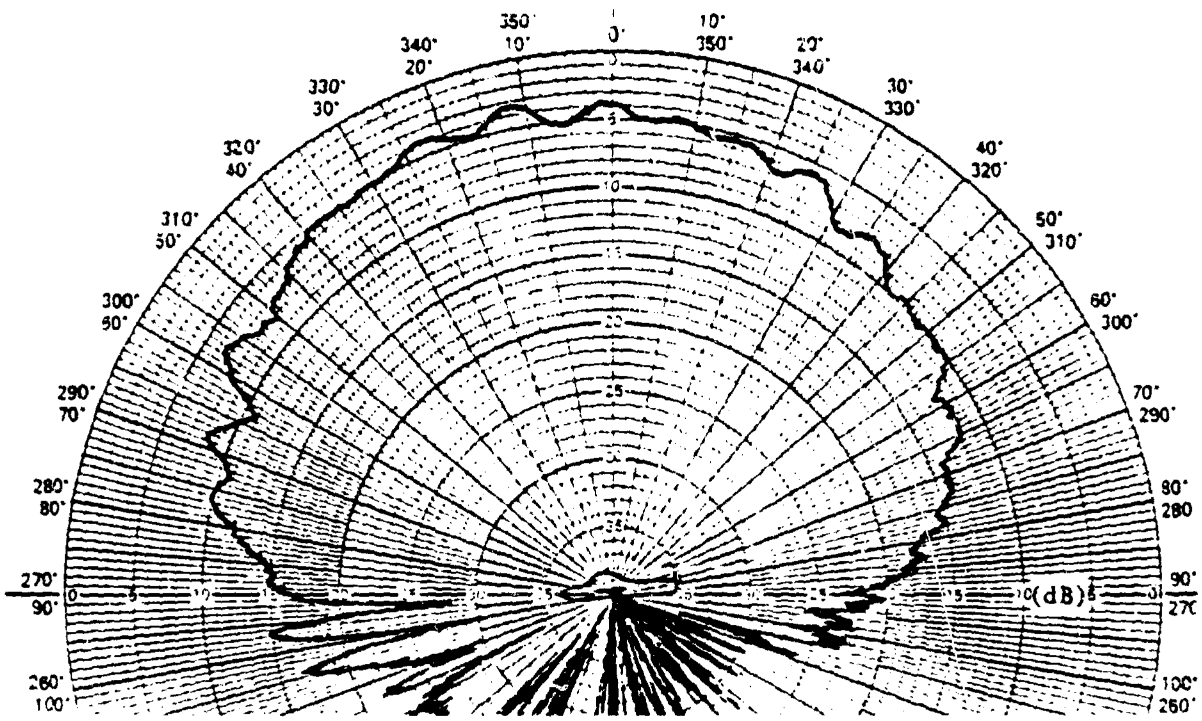


Pitch Plane

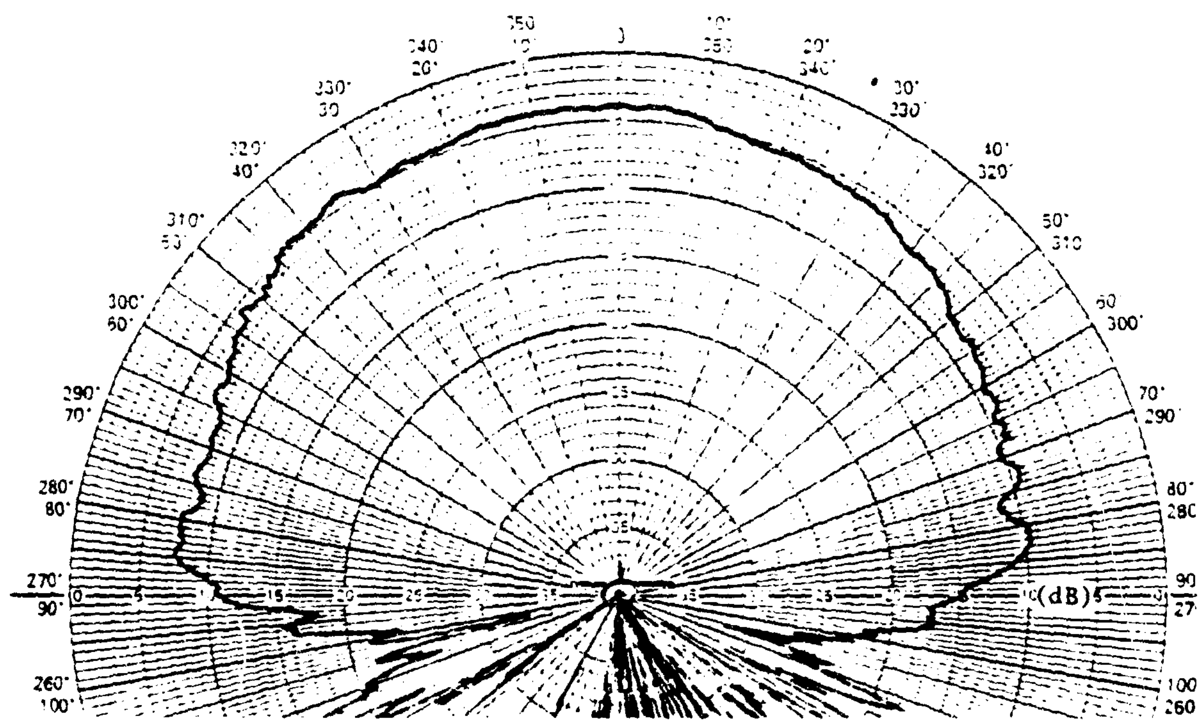


Roll Plane

Figure 2-6 Front Antenna Patterns from the Cessna 150 Model, 10,447 MHz

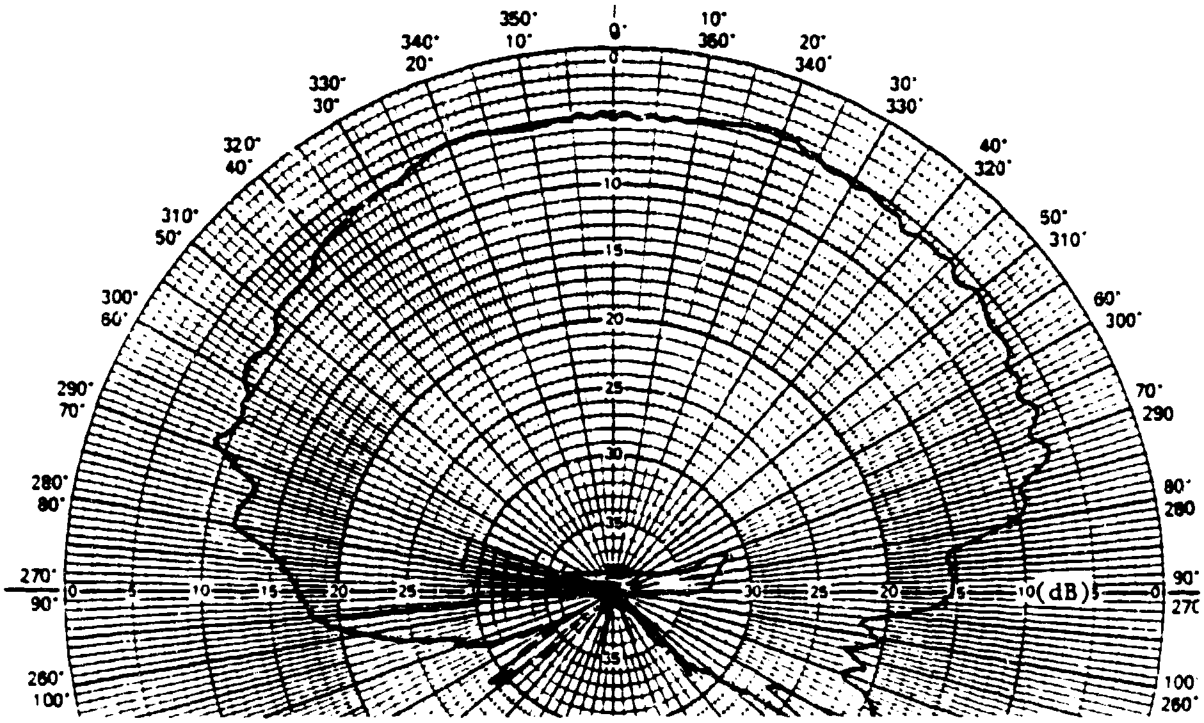


Pitch Plane

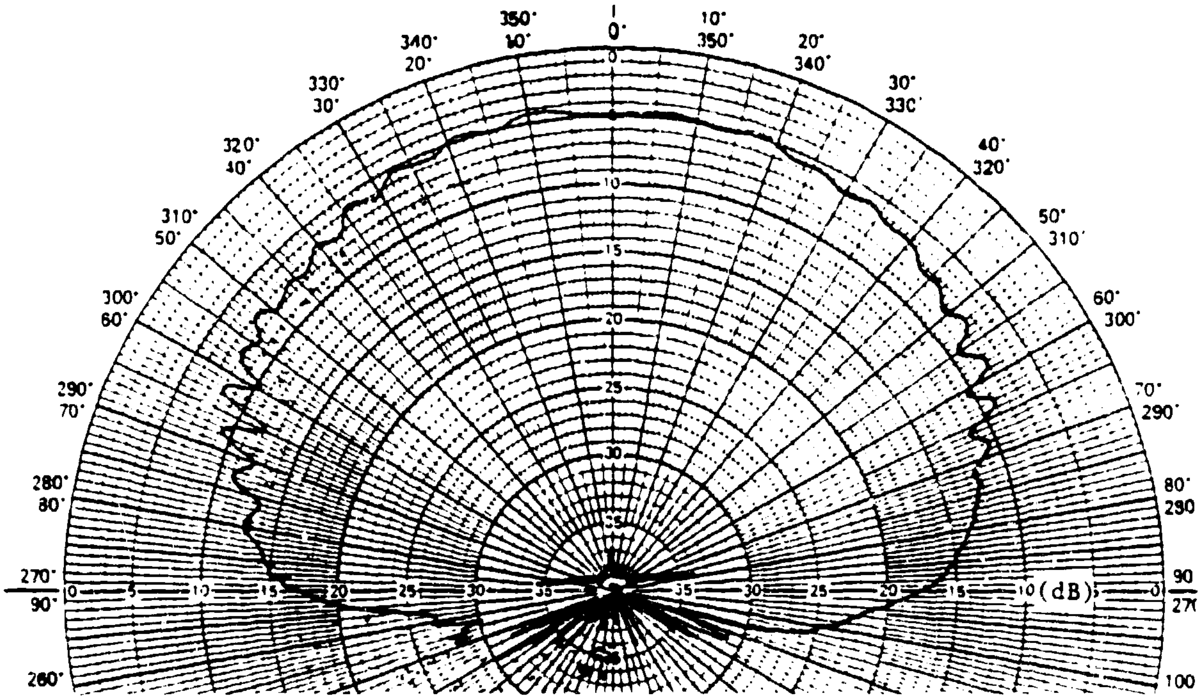


Roll Plane

Figure 2-7 Rear Antenna Patterns from the Cessna 150 Model, 10,870 MHz

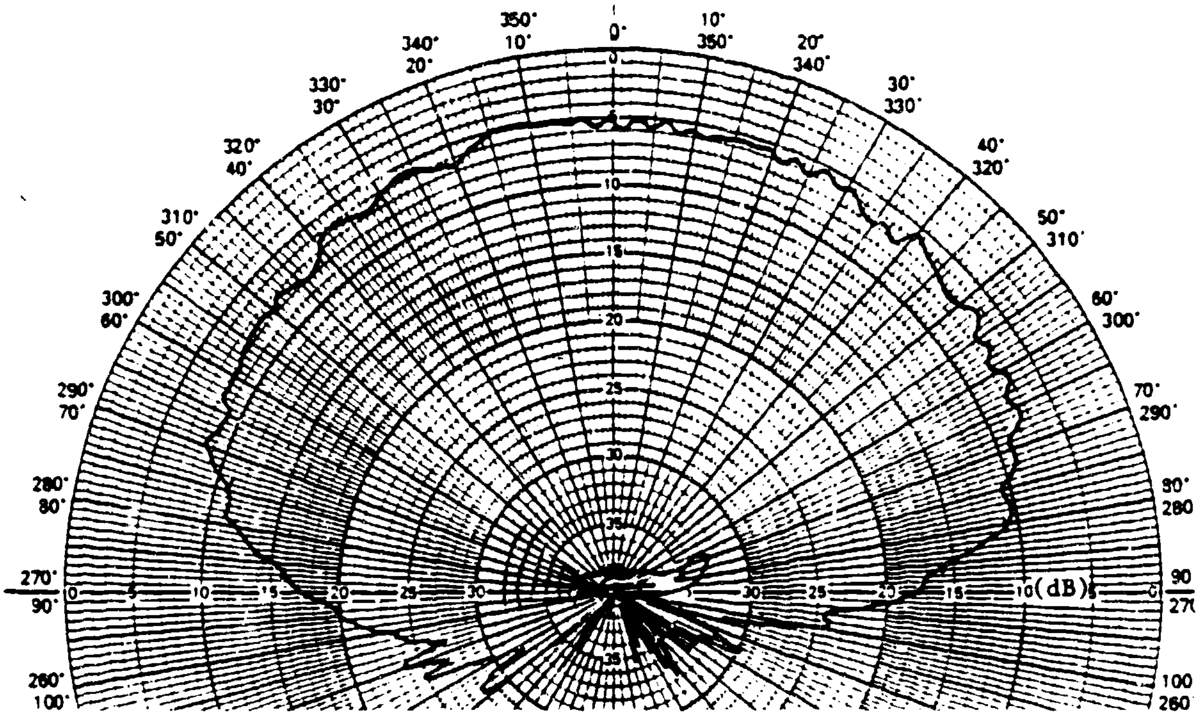


Pitch Plane

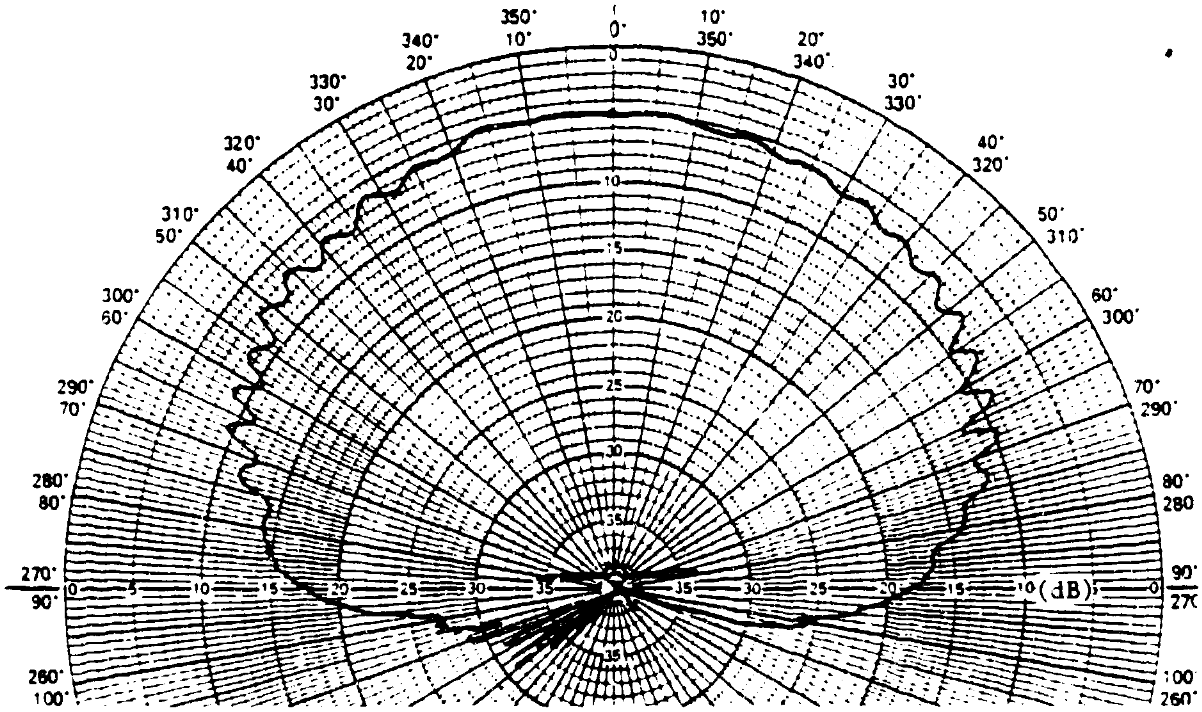


Roll Plane

Figure 2-8 Front Antenna Patterns from the Piper Cherokee Model, 10,828 MHz



Pitch Plane



Roll Plane

Figure 2-9 Rear Antenna Patterns from the Piper Cherokee Model, 10,780 MHz

Table 2-1

P RCENTAGE OF HEMISPHERE ABOVE GIVEN GAIN

Model	Location	Percent Above 0 dBi	Percent Above -5 dBi
Cessna 402B	front	71.4	100.0
	rear	75.5	100.0
Cessna 150	front	77.3	100.0
	rear	69.8	100.0
Piper Cherokee	front	67.6	94.2
	rear	69.6	95.2

3. DUAL-FREQUENCY CROSSED SLOT FOR GPS

The early work on dual-frequency crossed slot antennas suggested the possibility of a simple design etched on a single substrate layer using side-by-side, rather than stacked or other more complex designs. The motivation for this approach was the desire for a minimum cost antenna for small general-aviation aircraft. This element might not have the compactness required for an array application although it would be nearly ideal as a single, dual-frequency wide-beam width antenna. The concept was most obviously suited for GPS user vehicles. The potential advantages for this application appeared to be worthy of a limited developmental effort.

Specifically, the concept was to lay out 2 microstrip crossed slots, resonant at 1575 and 1227 MHz. The crossed slots were to be adjacent to each other on the same surface, as shown in Figure 3-1. The elements were to be fed from a common point, where the 1575-MHz element appeared as a very high impedance in parallel with the resonant impedance of the 1227-MHz element. Similarly, the 1227-MHz element would appear as a very high impedance in parallel with the resonant impedance of the 1575-MHz element.

The first working model performed very much as expected. Isolation between the two elements was good, and the patterns were as good as those measured on any other crossed-slot element. The low-frequency resonance was about 3 percent too high at 1231 MHz. A second model was laid out to correct the resonant frequency, and a third model was necessary to correct a feed-line error.

Impedance data for the GPS dual-frequency crossed slot are shown in Figure 3-2. The two frequencies were not perfectly centered; they were sufficiently close for this feasibility demonstration. Figures 3-3 and 3-4 show typical radiation patterns of the antenna mounted on a flat-ground plane 4 feet square.

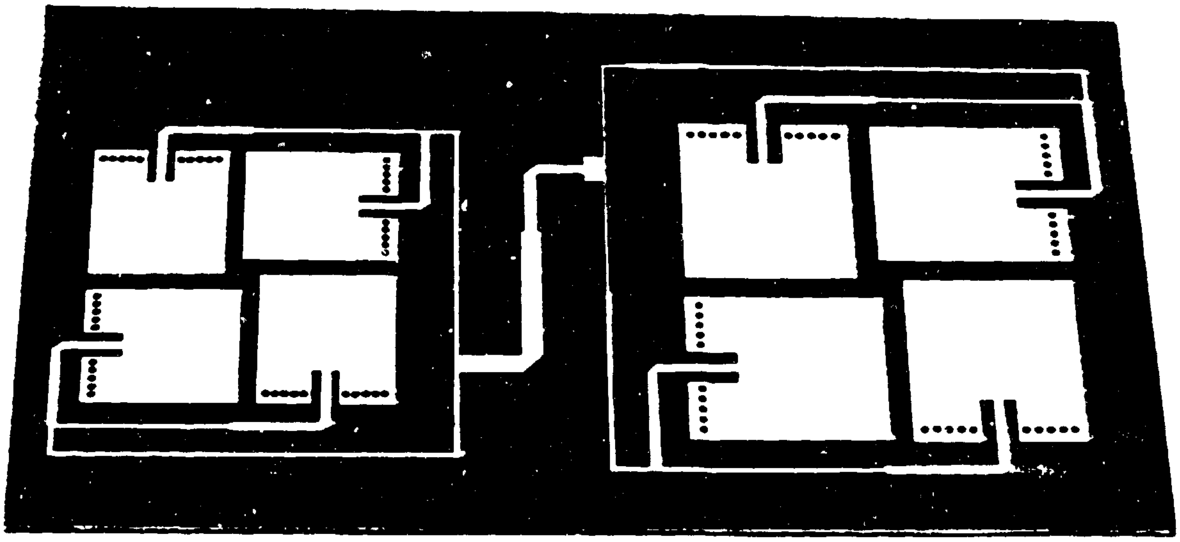


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Figure 3-1 Dual- Frequency Crossed-Slot Antenna

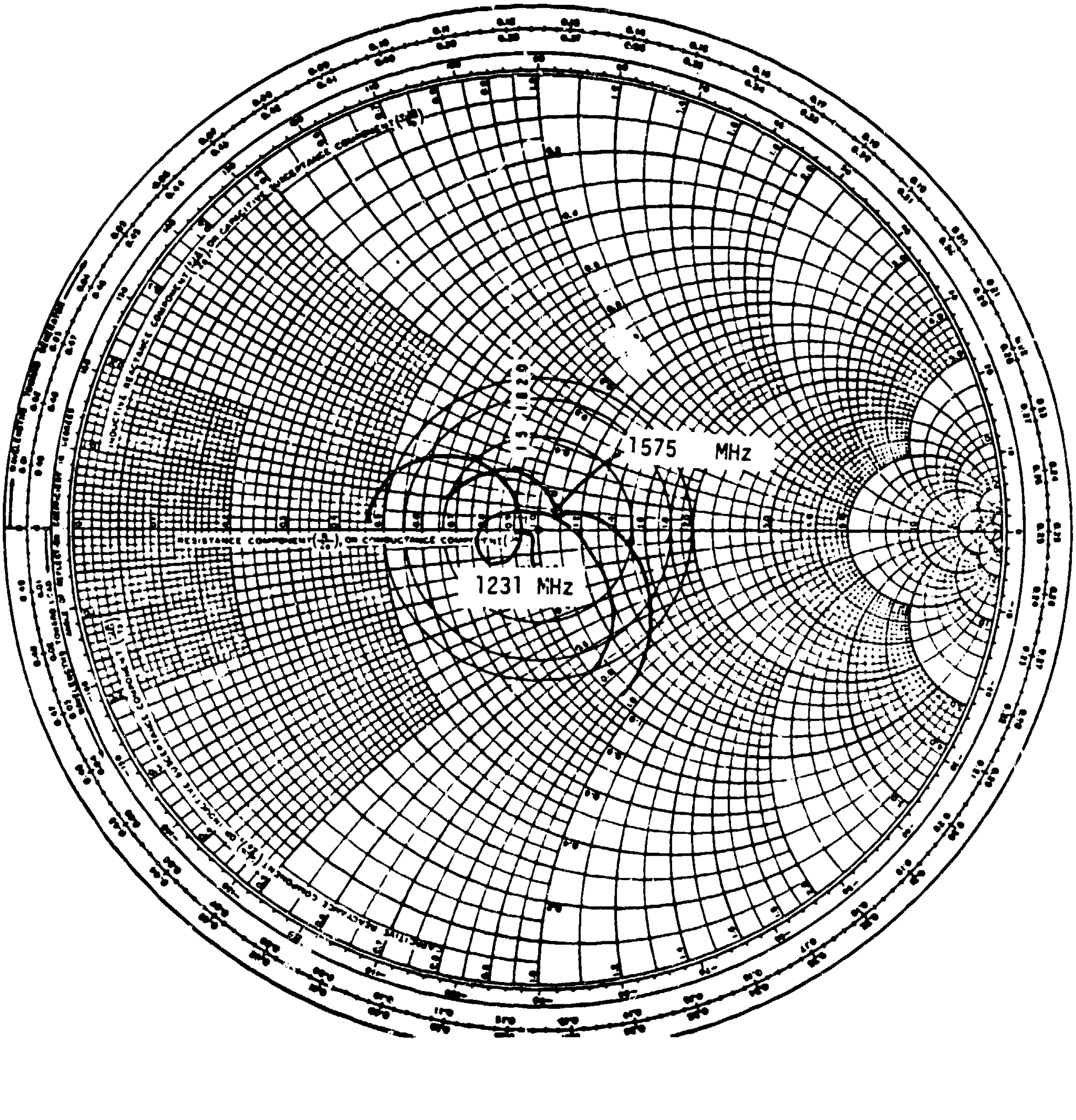


Figure 3-2 Input Impedance for the Dual-Frequency Crossed-Slot

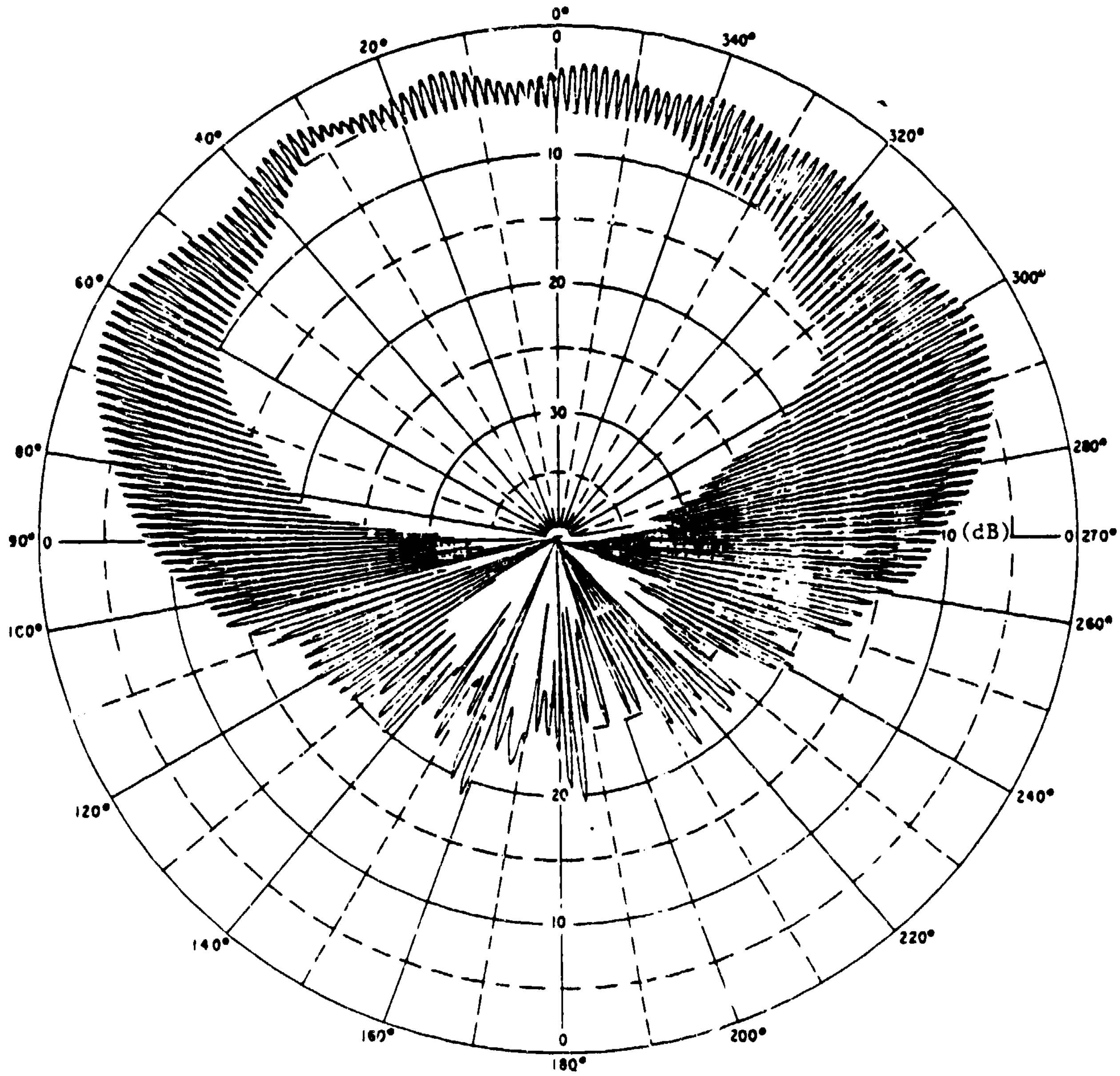


Figure 3-3 Radiation Pattern for the Dual-Frequency Crossed-Slot on a Square Ground Plane, 1575 MHz

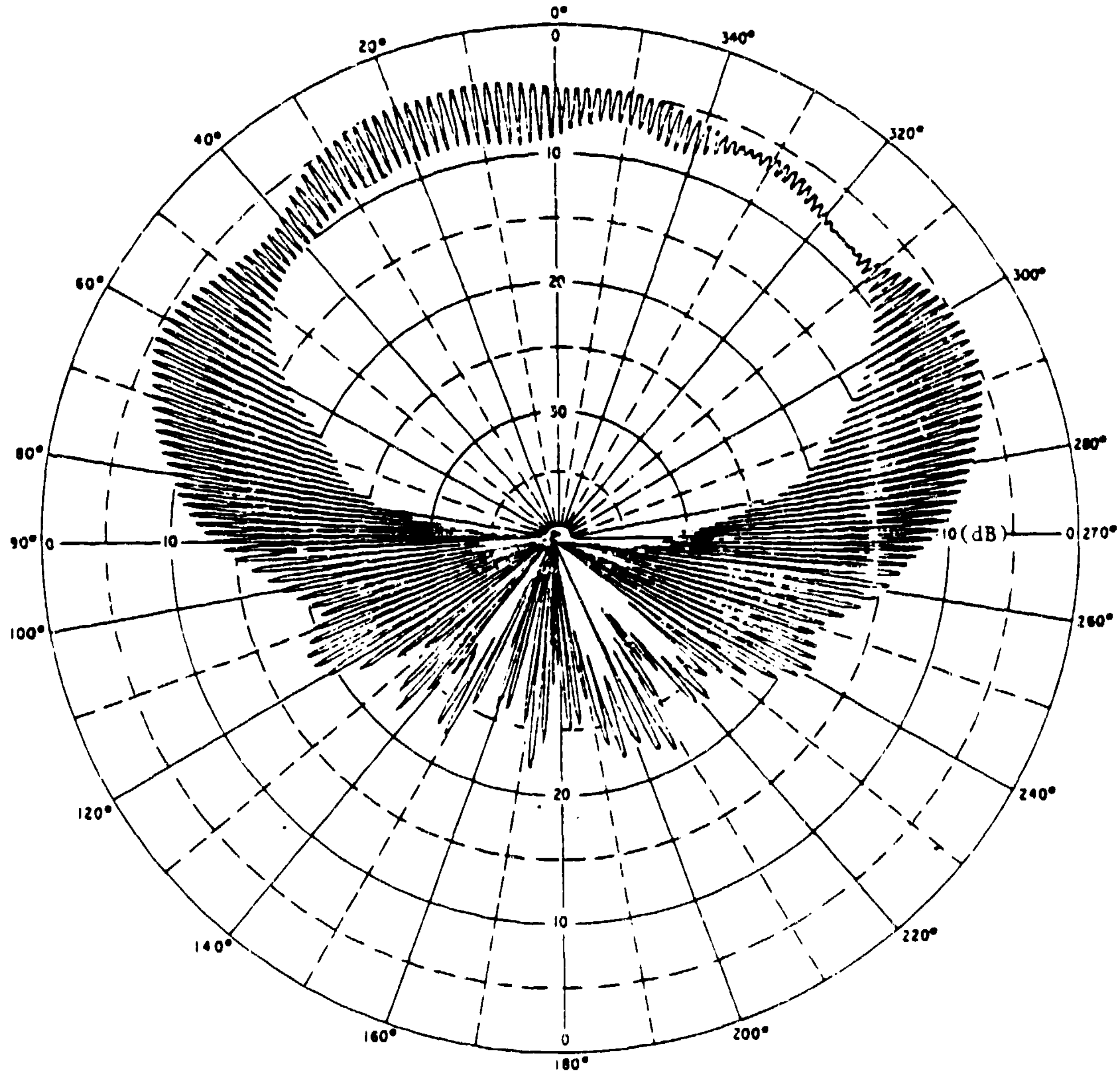


Figure 3-4 Radiation Pattern for the Dual-Frequency Crossed-Slot on a Square Ground Plane, 1234.5 MHz

4. STEERABLE BEAM GPS ANTENNA FOR GENERAL-AVIATION AIRCRAFT

4.1 BACKGROUND

The microstrip crossed-slot element was a natural choice for a low-cost antenna for G/A use with GPS. This design is a simple, low-cost, printed circuit element which produces a wide beam. However, the element by itself will not give continuous coverage of the majority of satellites because a large fraction of the total GPS satellite constellation is found below about 15 degrees elevation. The gain of the crossed-slot element decreases rapidly in this region due to the presence of the aircraft body. In addition, normal small pitch or roll maneuvers of the aircraft will cause loss of some satellite signals. It would be desirable to steer the wide beam electrically to compensate for aircraft motions. The steerable beam will produce an electronically stabilized pattern, or may be used to increase the gain in the direction of a satellite during level flight.

Several schemes for producing this steerable wide beam have been studied. Breadboards or simple engineering models have been built and tested, and the performance of each concept has been evaluated. Radiation-pattern measurements of the candidate designs have been made on a flat ground plane and a section of cylindrical ground plane (6-foot diameter). The combination of these measurements indicates an element's performance on an aircraft body in both the roll and pitch directions. The designs are compared based on performance, estimated cost and complexity, and the impact of installation on an aircraft. On the basis of these considerations, one of the designs--the sleeve monopole on a crossed slot--has been developed in detail, and an engineering model built for testing.

The design concepts studied included an array of circularly polarized microstrip elements arranged as the faces of a truncated pyramid. For a design based on this concept, steering would be accomplished by selecting one of the pyramid faces. A second design used for comparison was a three-element array of crossed slots wrapped on the aircraft fuselage. Beam steering in the roll

plane would be attained by selecting the proper element, however no provision exists for beam steering in the pitch plane using this approach. A third candidate element concept combined a monopole with a circularly polarized microstrip disc. The disc, with the monopole in its center, was mounted on a small pedestal to increase its beamwidth. It can be seen qualitatively that the typical dipole pattern of the monopole near the ground plane adds to the microstrip radiation to produce a broad composite pattern. Finally the element chosen for further tests was a crossed slot with a monopole in the center. Several configurations based on this concept were built and measured.

4.2 OVERVIEW OF CONCEPTS

4.2.1 Pyramid Array

This concept was borrowed from a standard technique for providing hemispherical coverage from a phased array. A four-side pyramid could be built with each side containing a single circularly polarized element. As the aircraft pitched or rolled, a switch would select one of the four sides to optimize upper-hemisphere coverage. In level flight, an element on the top of the pyramid would provide coverage (Figure 4-1). The antenna chosen for the element was a circularly polarized microstrip disc element on a high dielectric constant material. The use of the high dielectric constant acts to reduce the physical aperture and this material acts to reduce the physical aperture, and thus provides wider coverage from the element, and reduces the size of the pyramid.

Engineering-model tests of this concept consisted of patterns of a single element on a small ground plane. The angle between the element's ground plane and the vertical were changed to give the best coverage at horizon and lower angles. Also, the element height above the larger ground plane was increased to show its effect on the radiation pattern. These tests were performed on a section of 6-foot diameter ground plane. Both the pitch (cylinder axis) and roll (perpendicular to the cylinder axis) plane patterns were measured.

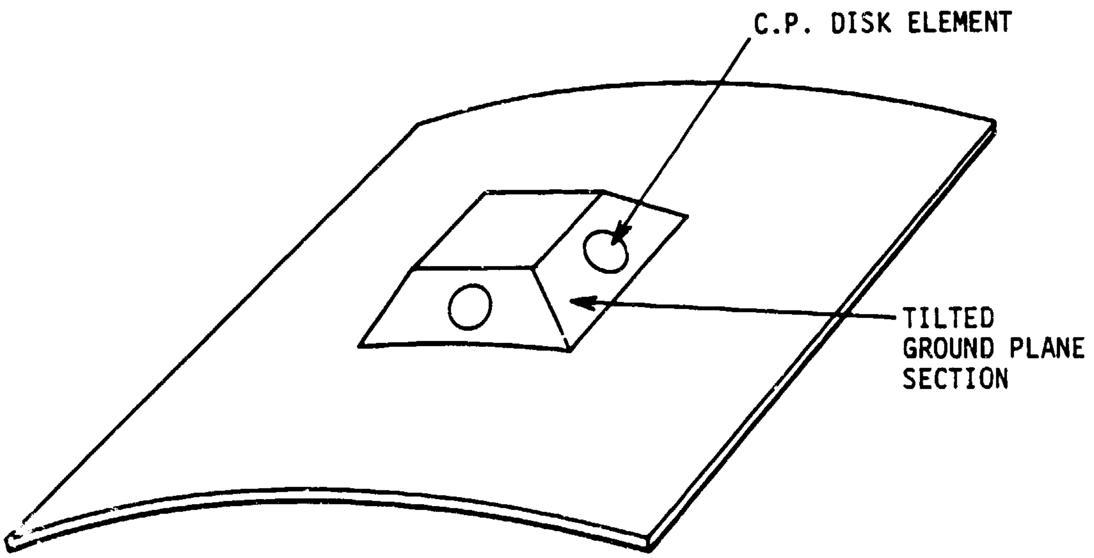


Figure 4-1 Pyramid Array

The results indicated that of the two angles (45 degrees and 60 degrees) tested, the angle nearer vertical produced more energy near the horizon. Also, as expected, increasing the element height above the curved ground plane provided better coverage. Figure 4-2 is a sample pattern of the element tilted at 45 degrees, about 2.5 inches above the ground plane. The coverage of this antenna, as with all the elements measured, improved in the roll plane.

The operational pyramid array on an aircraft needs associated electronics to determine the real horizon. Comparing this with the local horizon, an array face or faces will be selected to provide the best satellite viewing. While this antenna seems to offer the best coverage to low angles of the options considered, it is expected to be relatively complicated and expensive. In addition, the impact and cost of aircraft installation are believed to be high.

4.2.2 Wrapped Array of Crossed Slots

In contrast to the relative complexity of the pyramid array, an antenna consisting of three crossed slots wrapped circumferentially on the fuselage is simple. Excellent coverage can be obtained in the roll direction by spacing the three elements correctly on the aircraft body. As the aircraft is rolled about its axis for a turn, the element nearest the true vertical is selected. A simple one-pole, three-throw switch, a vertical sensor, and an actuator are all that is required.

While this element yields excellent roll coverage with a simple configuration, it performs identically to the crossed slot in the pitch plane. The array has no capability to correct for pitch motions.

4.2.3 Monopole on Crossed Slot

The first element of this concept consisted of a simple monopole mounted in the center of a crossed slot (Figure 4-3). Beam steering is accomplished

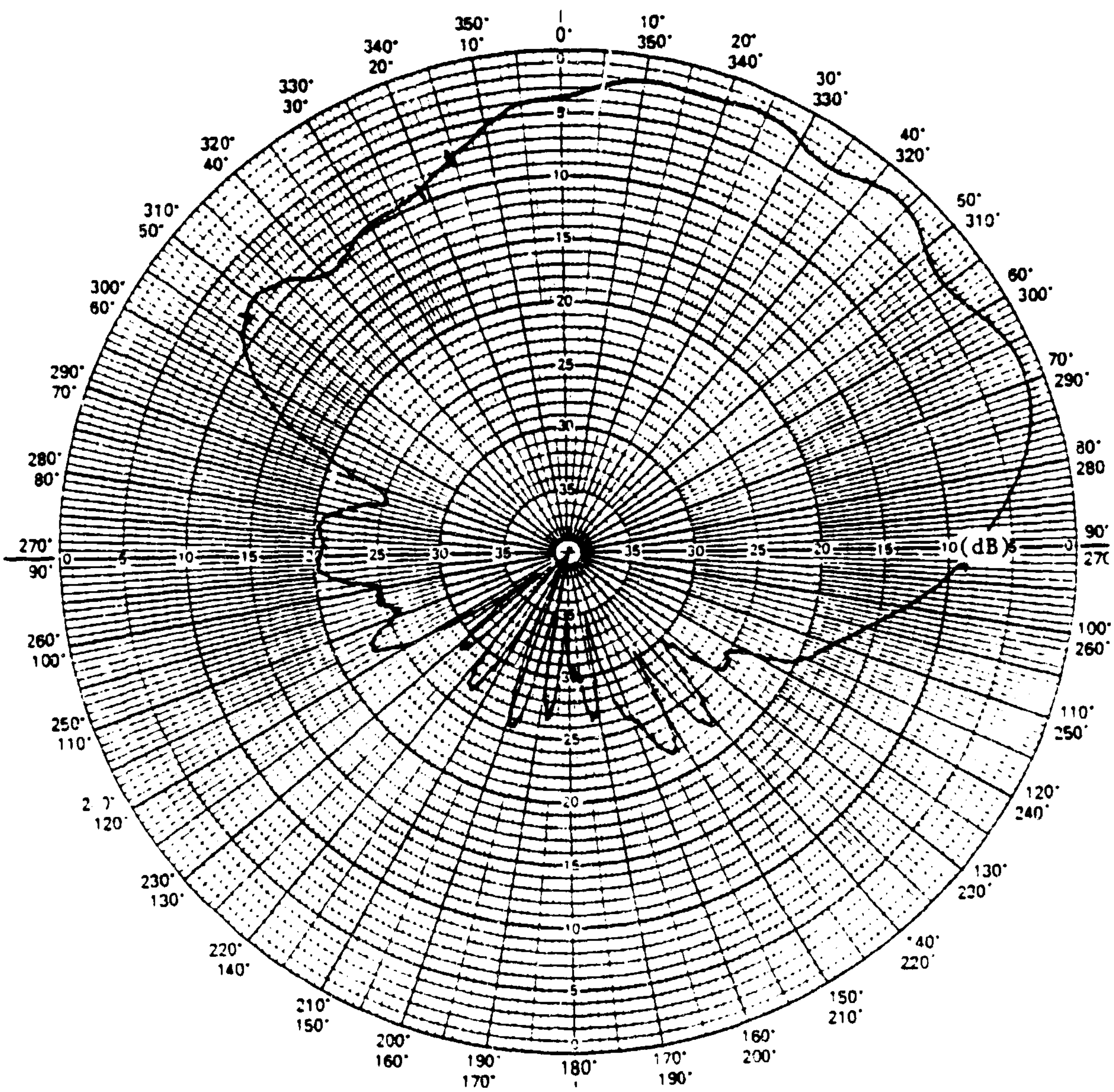
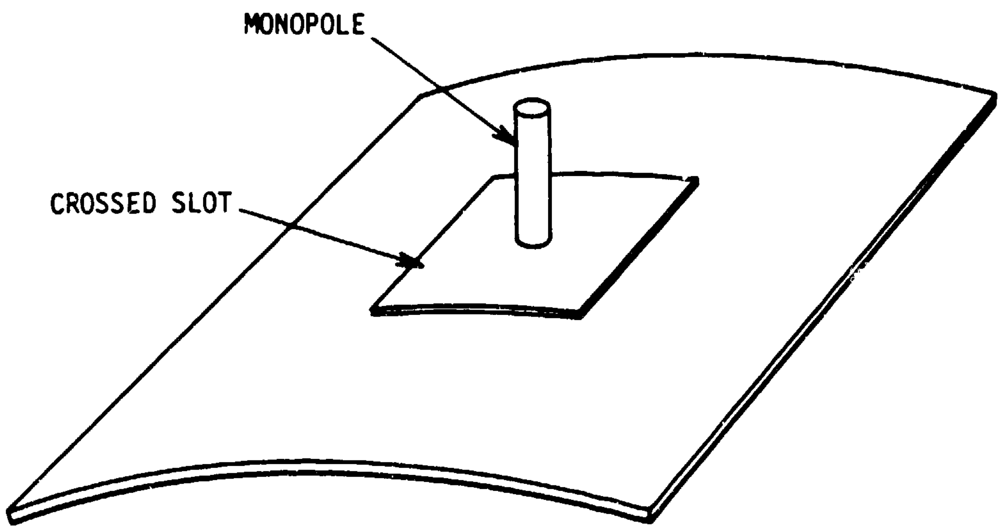


Figure 4-2 Radiation Pattern for a Single Element Tilted at 45^{0}, 1640 MHz



MONOPOLE WITH CROSSED SLOT

Figure 4-3 Monopole on a Crossed-Slot

by exciting both these elements with a certain amplitude and phase relationship. The radiation pattern of the crossed slot at angles near the ground plane is composed of a vertically polarized electric field. The phase of this electric field moves through a 360-degree variation around the crossed slot at a near-horizon elevation angle. This phase variation allows the monopole radiation (also vertically polarized) constructively and destructively to interfere with the crossed-slot pattern. Since the monopole exhibits no phase change in azimuth, its pattern will add to that of the crossed slot at some azimuth angle along the ground plane, and will subtract in the opposite direction. The elevation angle (angle from the vertical) at which this addition occurs is determined by relative amplitudes between the slot and monopole. The azimuth angle (angle around the monopole) is fixed by the relative phase of the excitations.

The steering achieved by this design moved the estimated 0 dBi level from 70 to 80 degrees from the vertical in elevation. This was achieved by splitting the power equally between the crossed slot and monopole. The peak of this pattern could be moved in azimuth by variation of the phase between the two elements. However, the cost in performance of the improved steering was a reduction in beamwidth in the elevation plane. The overall beamwidth in the plane narrowed from 140 degrees with no steering to approximately 110 degrees. A representative radiation pattern is shown in Figure 4-4.

The first attempt at improvement of the performance of the monopole and crossed slot is shown in Figure 4-5. In this design, the crossed slot is replaced with a circularly polarized microstrip element on a high dielectric substrate. The microstrip element is raised above the ground plane on a pedestal to increase its coverage. In addition, the raised pedestal improves the low-angle radiation from the monopole. Steering is achieved as described above. The measured data from this combination of elements show that the monopole pattern is very broad. This has produced interference nulls over a wide angular range when combined with the microstrip element. This concept has not been pursued further.

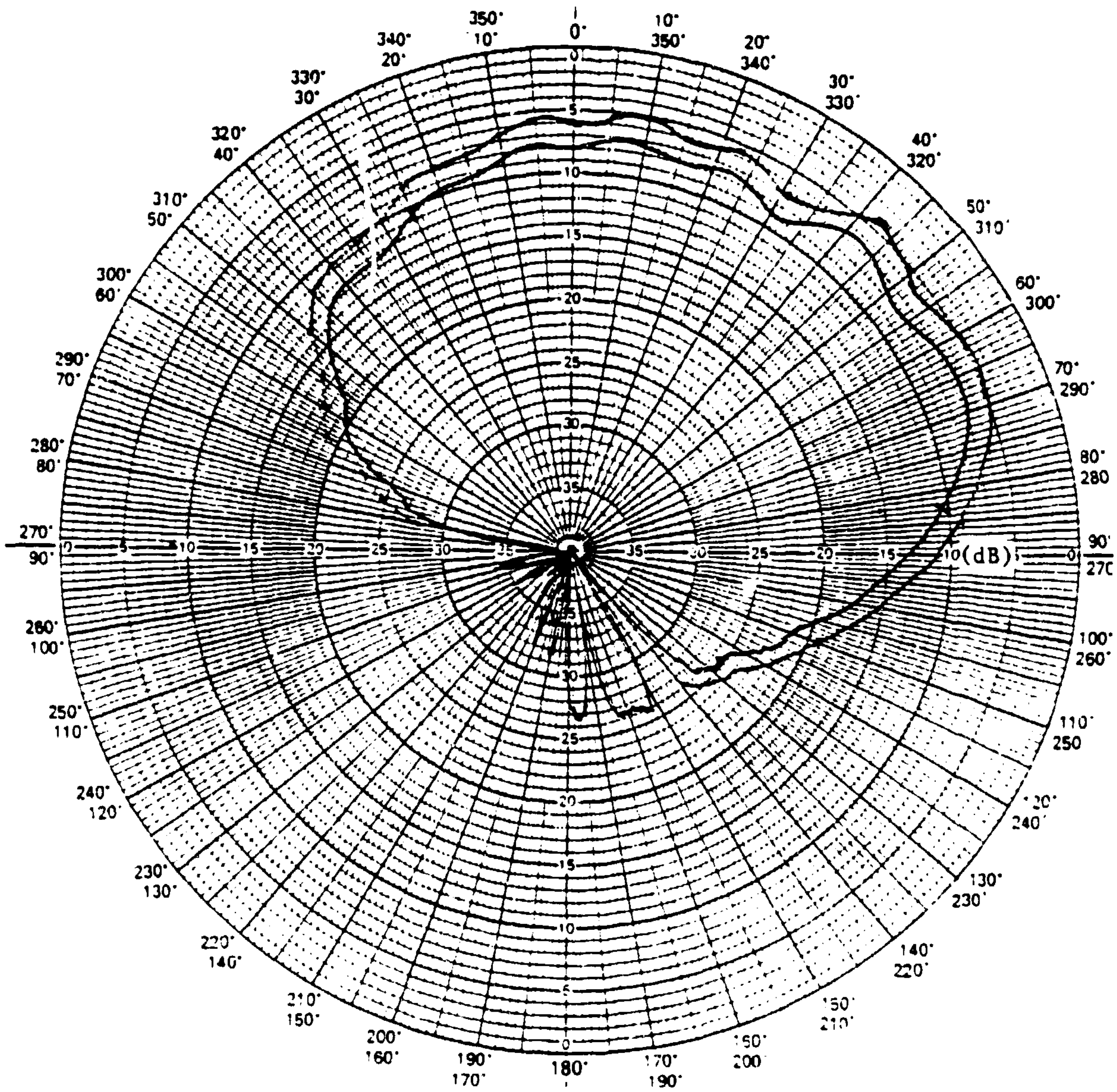


Figure 4-4 Radiation Pattern for the Monopole on Crossed-Slot, 1569 MHz

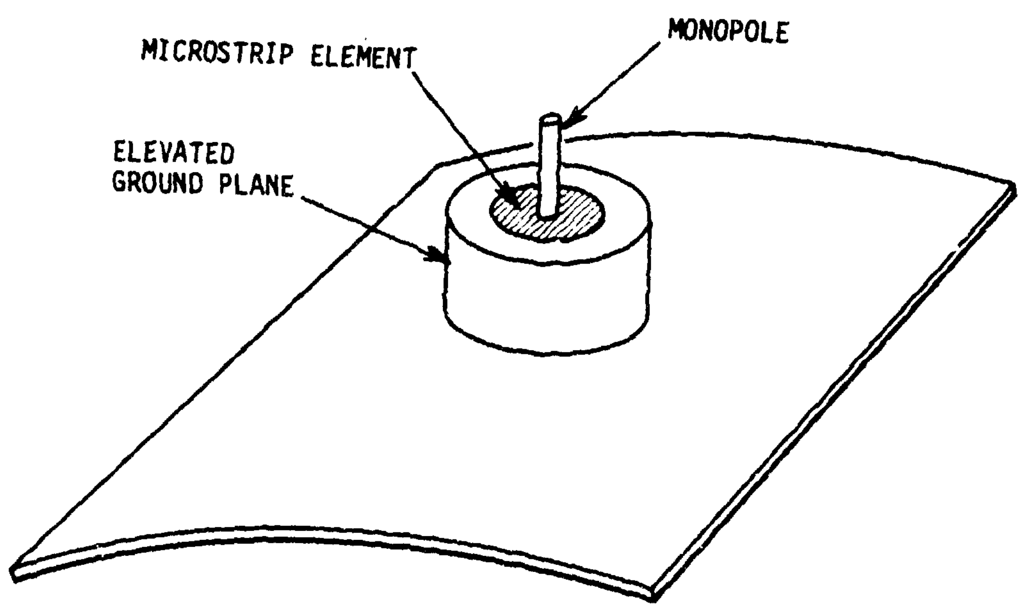
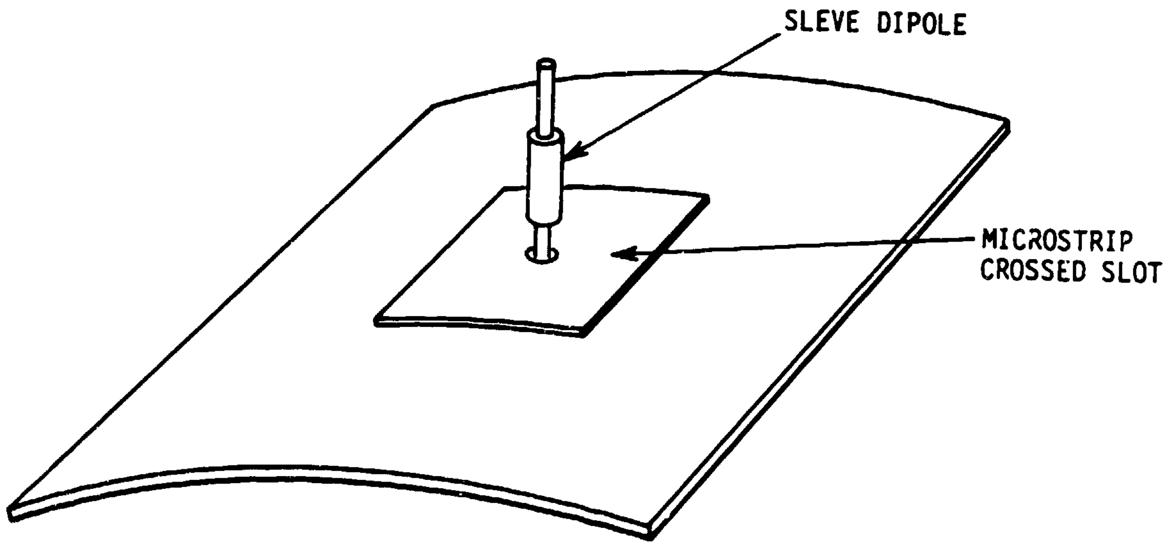


Figure 4-5 Monople with a Circularly-Polarized Element on Raised Ground Plane



SLEEVE DIPOLE WITH CROSSED SLOT

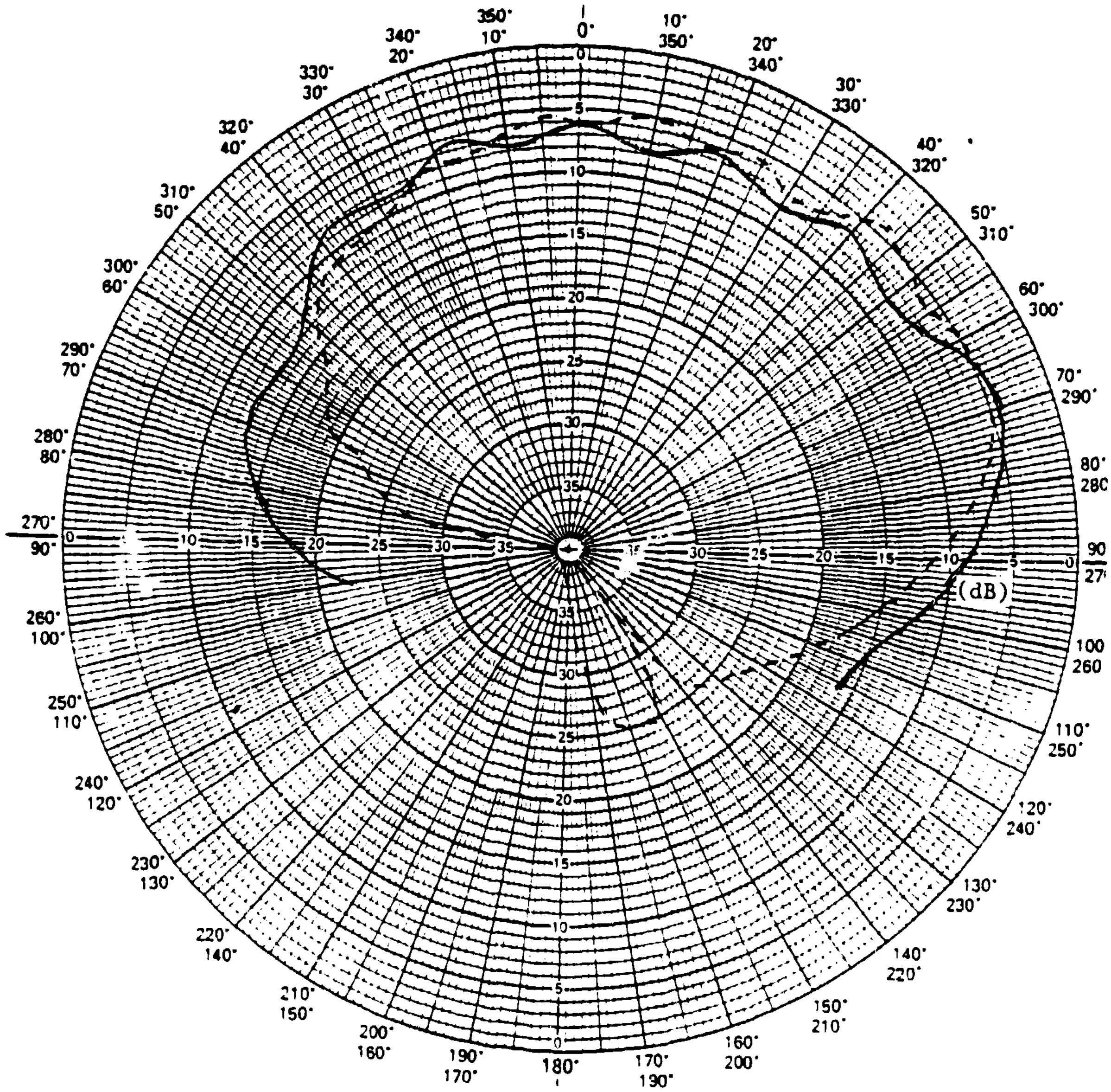
Figure 4-6 Sleeve Dipole on a Crossed-Slot

The third and successful attempt at improving the low angle radiation is depicted in Figure 4-6. In this design, the simple monopole is replaced by a taller sleeve dipole. The beamwidth of the sleeve dipole is narrower, concentrating its radiation near the horizon. The result is improved gain at low angles which improves the vertical-plane steering capabilities of the pair. An additional benefit is the broader beamwidth in the steered position which only decreases from 140 degrees to 130 degrees. This is also a result of the sleeve dipole's narrower pattern. Figure 4-7 is a radiation pattern of the crossed slot with sleeve dipole (shown in solid). Also on the figure is a pattern of the monopole and crossed slot shown for comparison.

On all of the engineering-model tests, no impedance matching or gain measurements were performed. The 0 dBi level was estimated from the measured gain of earlier versions of the crossed slot. Pattern measurements were made on a 4-foot square, flat-ground plane and on a 4-foot section of curved-ground plane (6-foot diameter). These were efforts to simulate the pitch and roll performance of a design.

4.3 CONCEPT TRADEOFFS

The steering performance of all the concepts was projected from radiation patterns measured on both a 4-foot-square ground plane and a section of a 6-foot-diameter curved ground plane. The data from the two tests were used to estimate the lowest angle that achieved a gain of 0 dBi or greater. Since impedance matching of these crude engineering models was not performed, the beamwidths of the radiation pattern were used to predict the 0 dBi level. The pyramid array provided the narrowest beam in both pitch and roll. The sleeve dipole/crossed-slot combination produced an 18-degree improvement (increase) in 0 dBi level beamwidth over the single crossed slot in the pitch plane and a 27-degree improvement in the roll plane. Any desired steering could be obtained in the roll plane from the switched crossed slots by suitable positioning of the elements. However, this concept offered only the performance of a single crossed slot in the pitch plane.



Crossed slot with sleeve dipole ———
Crossed slot with monopole - - - - - -

Figure 4-7 Radiation Pattern for the Sleeve Dipole on Crossed-Slot

Table 4-1

COMPARISON OF APPROACHES

	Ground Plane/Element	Steering	Complexity/Cost	Feed Loss	Installation Expense
I.	FLAT (Pitch Steering)				
A.	Single Crossed Slot	70°	Lowest	Lowest	Lowest
B.	Monopole/Crossed Slot	88°	Middle	Higher	High
C.	Pyramid Array	90°	Highest	High	Highest
D.	Switched Crossed Slots	70°	Middle	Middle	Middle
II.	CURVED (Roll Steering)				
A.	Single Crossed Slot	70°	Lowest	Lowest	Lowest
B.	Monopole/Crossed Slot	96°	High	Highest	High
C.	Pyramid Array	106°	Highest	High	High
D.	Switched Crossed Slots	119°	Middle	Middle	High

The performance of these concepts is compared to that of a single crossed slot in Table 4-1. Also, the estimated cost, losses, and installation expense are qualitatively presented in Table 4-1. The cost/complexity of the pyramid are highest primarily because of the difficult mechanical structure required to form the pyramid. It is believed that in large quantities this structure will be more expensive to produce than either the simple printed circuit of the switched crossed slots or the monopole/crossed slot combination. Although the phase shifter in the monopole/crossed slot is more complex electronically than the single SPST switch of the pyramid array, the cost of producing this monolithic microstrip device in quantity is believed to be low. The printed circuit nature of the monopole/crossed slot should permit a cost reduction in even relatively complex circuits.

In estimating the feed losses of the various designs, the highest loss was assigned to the monopole/crossed slot element because of the type of feed line (microstrip) used. However, the effect of the feed system loss on the gain should be small since a short length was used in the phase-shifter design. The connections between the elements on the pyramid array and the switch could be made with low-loss coaxial cables.

Finally, the principal factor in determining the impact of installation of the candidate designs is the relative aerodynamic drag. The pyramid array presents the largest cross section to the direction of flight, and will require the stiffest fastening to the aircraft skin. The dipole/crossed slot will have a lower drag response because of the small relative cross section of the sleeve dipole. A fairing may be added both to improve the aerodynamics of the element and to add mechanical support. Finally, the single crossed slot and switched crossed slots will have negligible drag when correctly fastened to the aircraft. The large size of the switched crossed slot will require more fasteners than the other types.

A steering calculator will be required for all steerable beam concepts. The calculator will need to sense the true horizon and compute the required switching or phase shifting for the antenna. This device will be relatively simple since only one of at most eight possible choices can be made. The

pyramid array has five faces from which to choose, and the monopole/crossed slot has eight possible phase states or beam positions.

The monopole/crossed slot element has been chosen for further study because of its relative performance and cost. This design, using a sleeve dipole and three-bit phase-shifter, provides improved pattern coverage without a large increase in element or installation costs.

4.4 ENGINEERING-MODEL MEASUREMENTS

4.4.1 Construction Details

An engineering model of a sleeve dipole over a crossed slot was constructed and tested. Figure 4-8 shows the microstrip antenna and the phase-shifter circuitry associated with the combination. It is noted that the crossed slot and phase shifter/switch are fabricated with a single etching operation, following preparation of the plated-through holes. The microstrip crossed slot is fed directly from the input connector. The monopole is fed through a three-bit switched-line phase shifter and switch. The switch serves to turn the sleeve dipole entirely on or off, and the phase shifter serves to steer the beam. In this engineering model, the power is not split evenly between the sleeve dipole and the crossed slot due to the difference in line lengths (and attendant losses) to the two elements.

Figure 4-9 shows the completed antenna. The sleeve dipole is centered between the microstrip crossed slots.

4.4.2 Impedance Measurements

To hold a reasonable impedance match, the antenna is designed for a feed-point impedance of 70Ω with the sleeve dipole off and 35Ω with the monopole on (1.4:1 VSWR). Figure 4-10 is a plot of the antenna input impedance with the sleeve dipole off, and Figure 4-11 is a plot with the sleeve dipole on. As

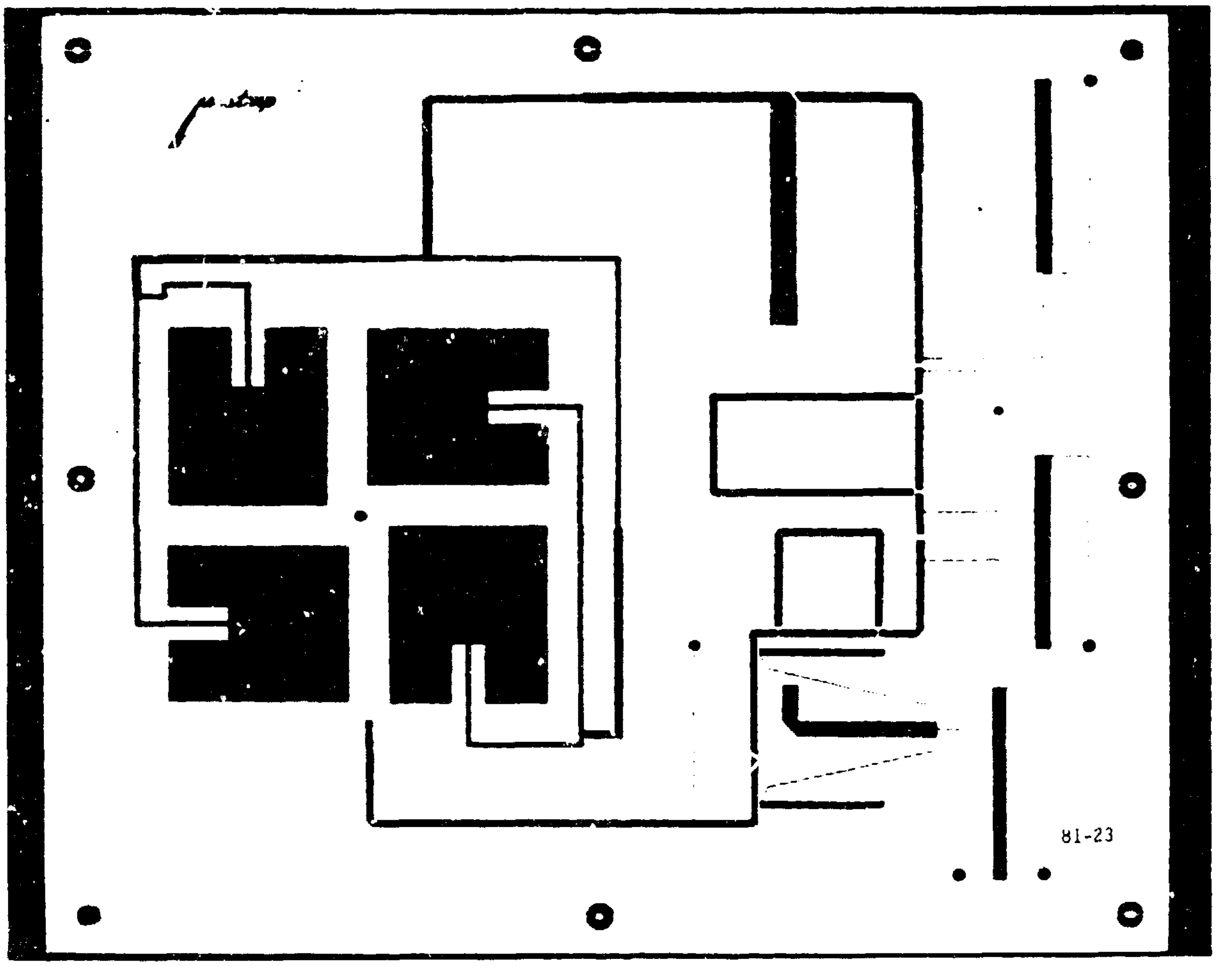


Figure 4-8 Microstrip Crossed-Slot and Phase-Shifter

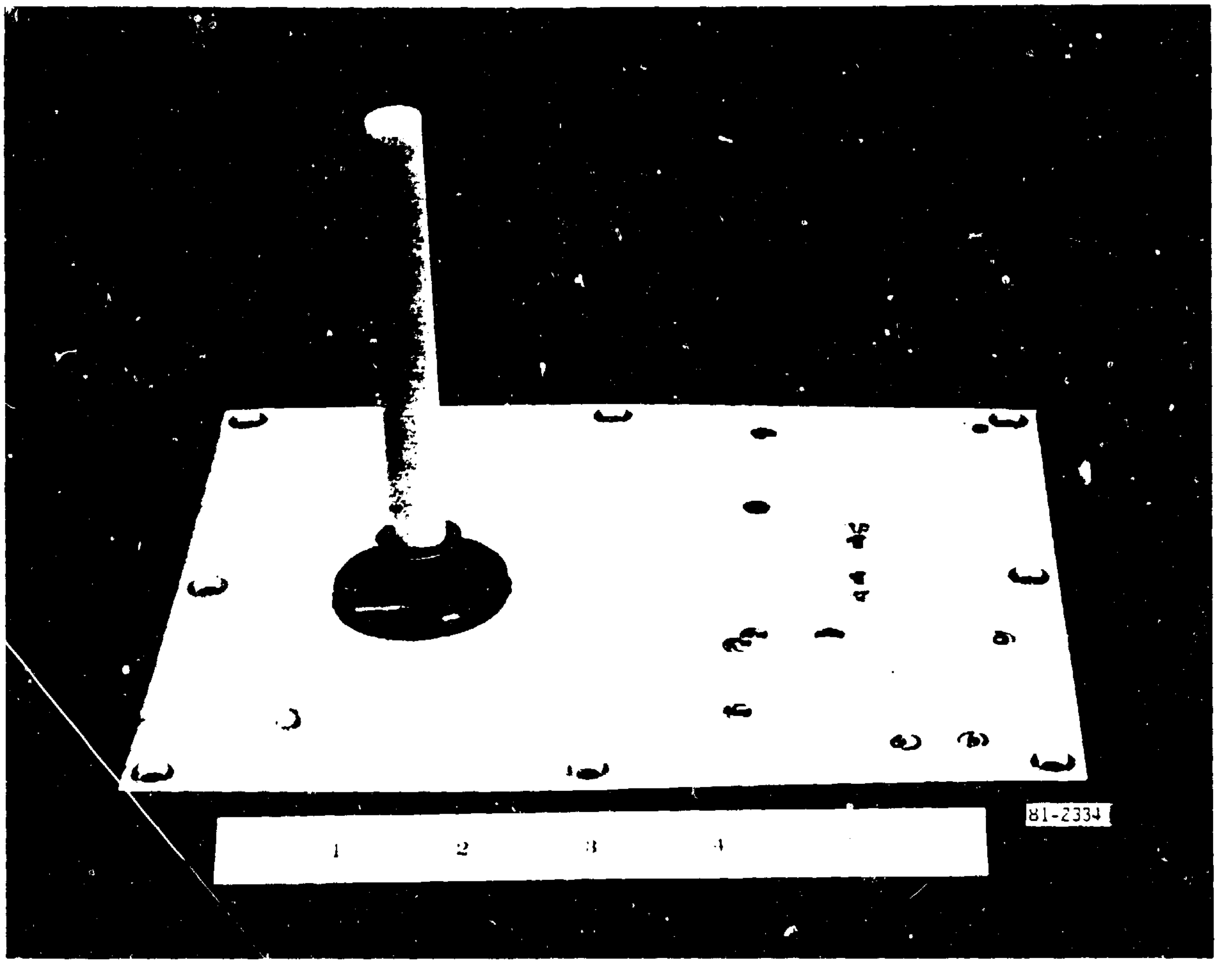


Figure 4-9 Sleeve Dipole Over a Microstrip Crossed-Slot

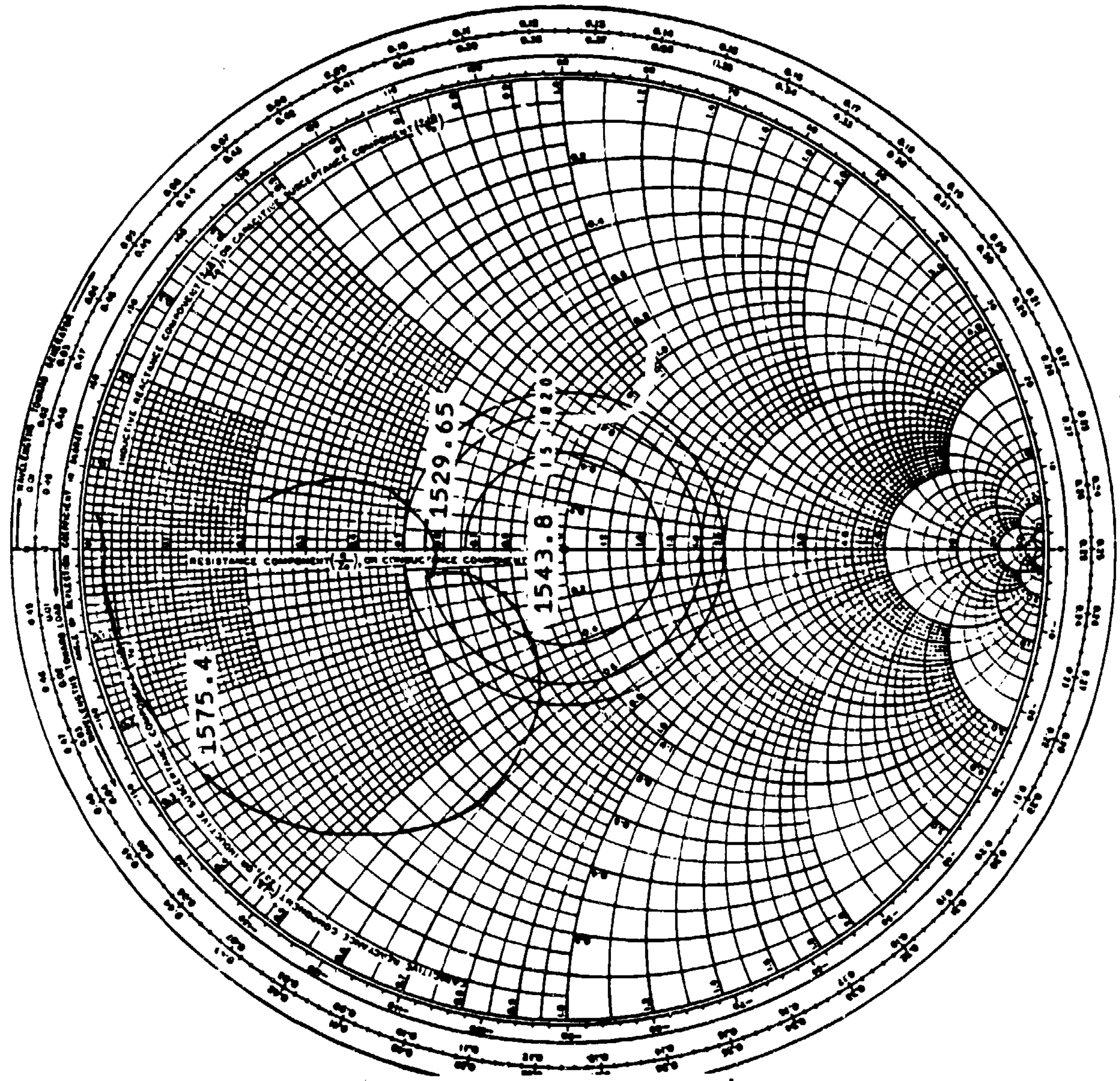


Figure 4-10 Input Impedance with the Sleeve Dipole Off

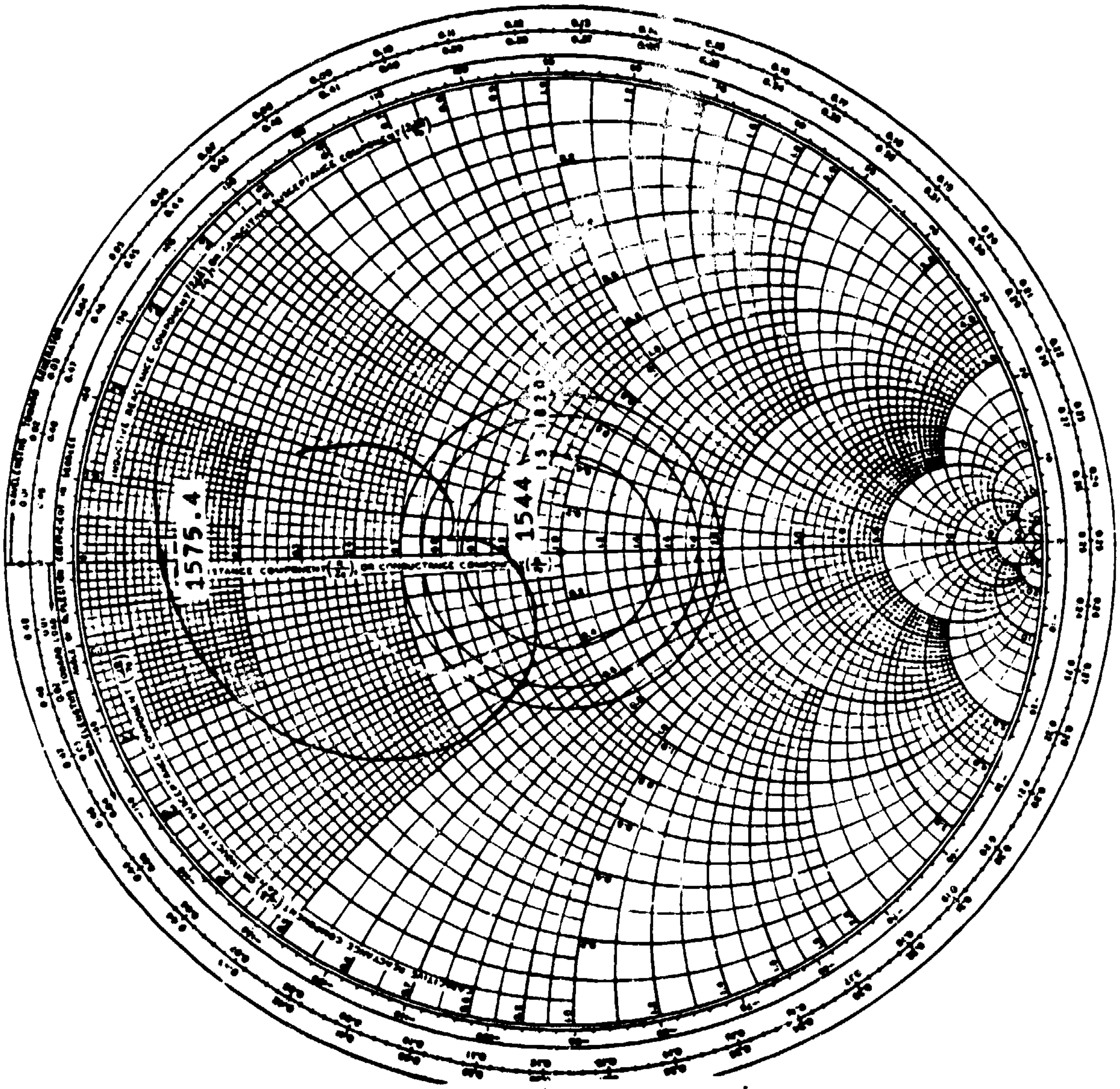


Figure 4-11 Input Impedance with the Sleeve Dipole On

can be seen from these plots, the antenna is operating slightly low in frequency. This off-frequency operation may be easily corrected by scaling down the radiating element lengths.

4.4.3 Pattern Measurements

The sleeve dipole/crossed slot is mounted on a 4-foot square ground plane for pattern measurements. Patterns are measured in 2 orthogonal planes for each phase-shift bit. To determine the positions of the 2 planes, the antenna pattern is measured on a conical cut up 20 degrees from the antenna horizon. The patterns thus obtained exhibit a null in 1 direction. This null is 180 degrees from the peak of the beam. The 2 orthogonal planes are then selected to be through and at right angles to this null. Figures 4-12 and 4-13 are patterns for the sleeve dipole/crossed slot measured in this manner.

4.4.4 Recommendations for Further Refinements

The microstrip crossed slot should be brought up in frequency by proper scaling of dimensions. The degree of frequency scaling required was a function of the particular substrate material used, and could only be determined from tests on that substrate.

The sleeve dipole should be fed with the same amount of power as the crossed slot. The correct power division could be made by equalizing the line lengths to the two elements (resulting in a slightly less efficient antenna), or by using a pair of transformers to feed more power to the monopole. If the method incorporating the transformers were used, some provision should be made for a stable feed-point impedance.

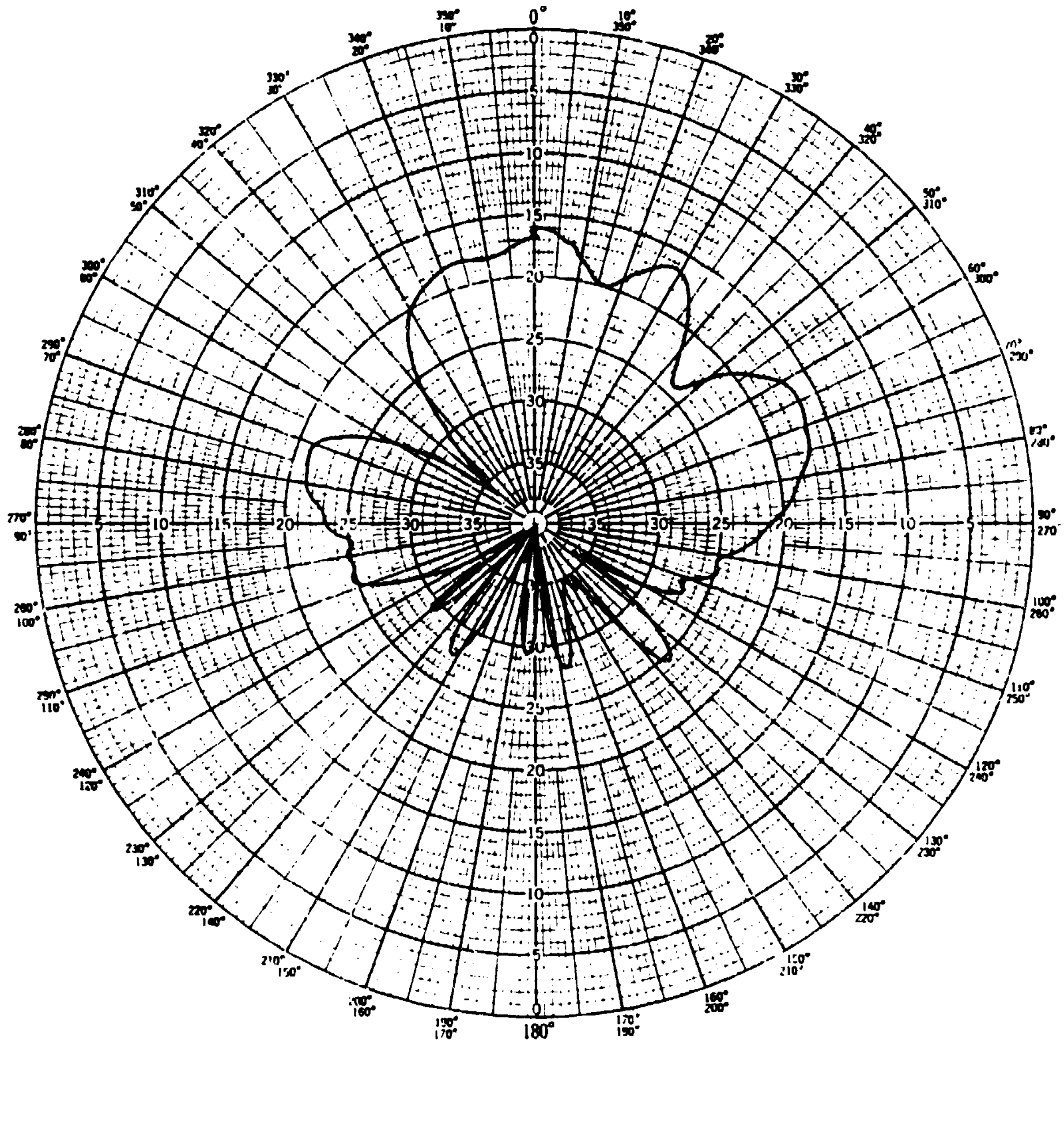


Figure 4-12 Pattern of the Sleeve Dipole/Crossed Slot taken through the Null.

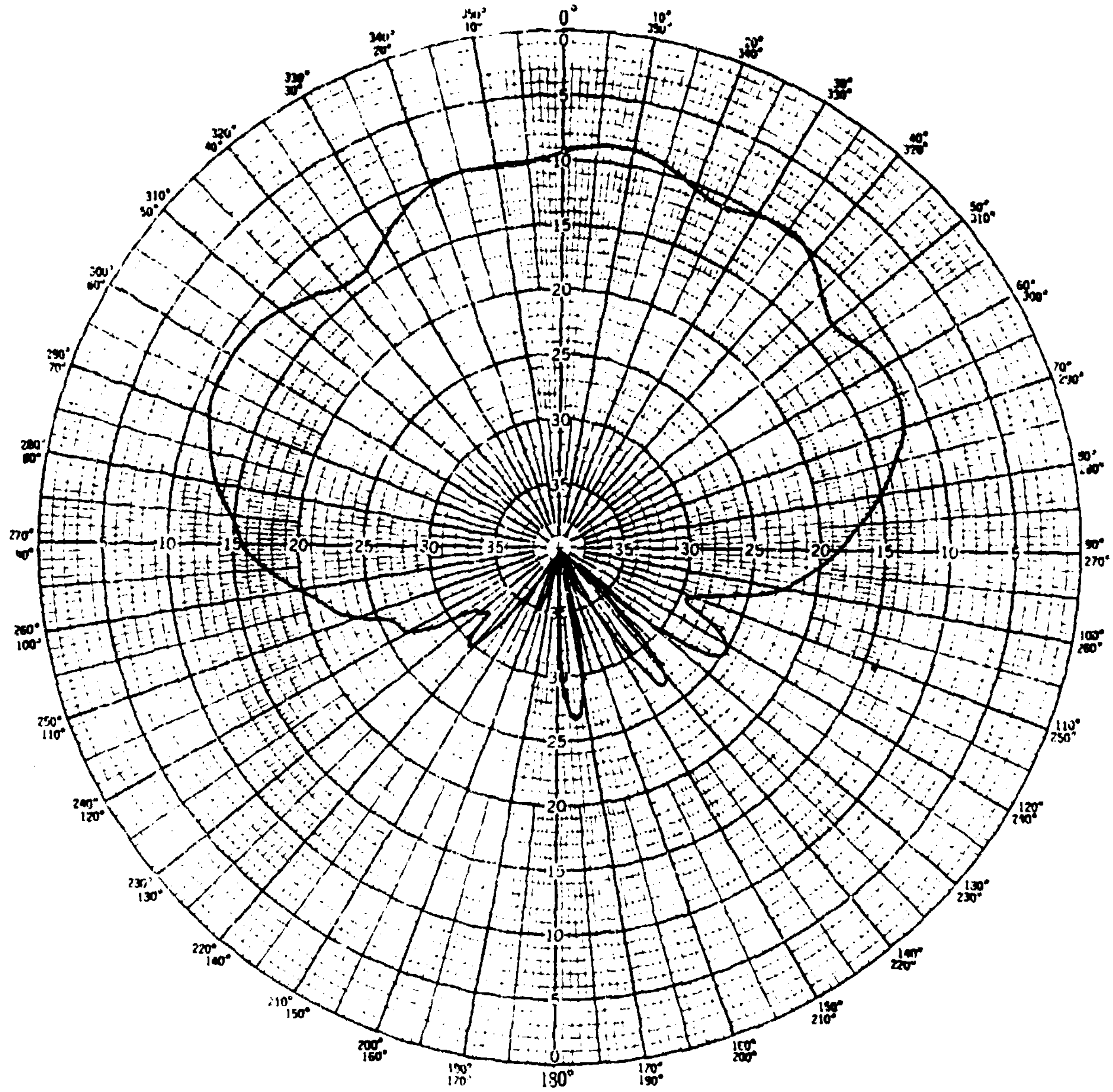


Figure 4-13 Pattern at the Sleeve Dipole/Crossed Slot taken at Right Angles to the Null.

APPENDIX

REPORT OF NEW TECHNOLOGY

Work performed under this contract has advanced the state of the art in conformal antenna design. A list of accomplishments includes the following:

a) first all-microstrip crossed slot,

b) unique dual-frequency crossed slot designs,

c) use of high dielectric constant to broaden beamwidth,

d) simplified conformal end-fire array, and

e) adaptation of phase shifter to dual-frequency operation.

Nevertheless, a diligent review of the work has revealed no innovation, discovery, improvement, or invention, other than those previously patented.

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